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**Contrasting styles of post-caldera volcanism along the Main Ethiopian Rift:**

**Implications for contemporary volcanic hazards**

Karen Fontijn<sup>1,\*</sup>, Keri McNamara<sup>2</sup>, Amdemichael Zafu Tadesse<sup>3</sup>, David M Pyle<sup>1</sup>, Firawalin Dessalegn<sup>4</sup>, William Hutchison<sup>5</sup>, Tamsin A Mather<sup>1</sup>, Gezahegn Yirgu<sup>3</sup>

<sup>1</sup>Department of Earth Sciences, University of Oxford, United Kingdom

<sup>2</sup>School of Earth Sciences, University of Bristol, United Kingdom

<sup>3</sup>School of Earth Sciences, Addis Ababa University, Ethiopia

<sup>4</sup>Department of Geology, Wollega University, Ethiopia

<sup>5</sup> School of Earth and Environmental Sciences, University of St. Andrews, United Kingdom

\*Corresponding author: Karen.Fontijn@earth.ox.ac.uk, karen.fontijn@gmail.com, Tel +44 1865 272045

**Abstract**

The Main Ethiopian Rift (MER, ~7-9 °N) is the type example of a magma-assisted continental rift. The rift axis is populated with regularly spaced silicic caldera complexes and central stratovolcanoes, interspersed with large fields of small mafic scoria cones. The recent (latest Pleistocene to Holocene) history of volcanism in the MER is poorly known, and no eruptions have occurred in the living memory of the local population. Assessment of contemporary

22 volcanic hazards and associated risk is primarily based on the study of the most recent  
23 eruptive products, typically those emplaced within the last 10-20 ky. We integrate new and  
24 published field observations and geochemical data on tephra deposits from the main Late  
25 Quaternary volcanic centres in the central MER to assess contemporary volcanic hazards.

26 Most central volcanoes in the MER host large mid-Pleistocene calderas, with typical  
27 diameters of 5-15 km, and associated ignimbrites of trachyte and peralkaline rhyolite  
28 composition. In contrast, post-caldera activity at most centres comprises eruptions of  
29 peralkaline rhyolitic magmas as obsidian flows, domes and pumice cones. The frequency  
30 and magnitude of events varies between individual volcanoes. Some volcanoes have  
31 predominantly erupted obsidian lava flows in their most recent post-caldera stage (Fentale),  
32 whereas others have had up to 3 moderate-scale (VEI 3-4) explosive eruptions per  
33 millennium (Aluto). At some volcanoes we find evidence for multiple large explosive  
34 eruptions (Corbetti, Bora-Baricha, Boset-Bericha) which have deposited several centimetres  
35 to metres of pumice and ash in currently densely populated regions. This new overview has  
36 important implications when assessing the present-day volcanic hazard in this rapidly  
37 developing region.

#### 38 **Key words**

39 Main Ethiopian Rift; volcanic hazards; calderas; peralkaline rhyolite; explosive eruptions

40

## 41       **1. Introduction**

### 42       **1a. Volcanic hazards in East Africa**

43       The East African Rift System (EARS) is the classic example of a continental rift system  
44       associated with active volcanism (Ebinger 2005). Magmatic systems along the densely  
45       populated EARS remain active, as demonstrated by historical eruptions (Siebert et al. 2010),  
46       active degassing (Bluth and Carn 2008; Hutchison et al. 2015; Robertson et al. 2016), recent  
47       ground deformation at multiple volcanoes (Biggs et al. 2009, 2011; Hutchison et al. 2016a;  
48       Wauthier et al. 2013), seismicity (e.g. Keir et al. 2006; Wilks et al. 2017) and ubiquitous  
49       evidence for Late Quaternary explosive eruptions in the form of tephra deposits in  
50       terrestrial and lacustrine archives (Barker et al. 2003; Blegen et al. 2015; Chalié and Gasse  
51       2002; Fontijn et al. 2010, 2012; Hutchison et al. 2016b; Leat 1984; Le Turdu et al. 1999;  
52       Martin-Jones et al. 2017; Pyle 1999; Rapprich et al. 2016; Scott 1980). Detailed volcanic  
53       hazard assessments and/or ground-based monitoring efforts are, however, almost non-  
54       existent, raising concerns in light of population growth and the rapid expansion of  
55       geothermal infrastructure on active volcanoes (Aspinall et al. 2011; USAID 2017). A recent  
56       assessment of global volcanic risk identified Africa as a region with high population exposure  
57       combined with high vulnerability (Auken et al. 2015).

58       Prior studies at individual rift volcanoes in the EARS suggest late Pleistocene recurrence  
59       rate for explosive eruptions of order of 500 – 1000 years at silicic centres such as the  
60       trachytic Rungwe and Ngozi volcanoes in southern Tanzania (Fontijn et al. 2010, 2012) and  
61       the peralkaline rhyolitic complexes of Aluto (Hutchison et al. 2016b) and Corbetti (Martin-  
62       Jones et al. 2017) in Ethiopia. These long repose times and the absence of any memory of



63 past explosive eruptions presents challenges for the communication of volcanic hazards risk,  
64 both for local communities and the authorities (e.g. Donovan and Oppenheimer 2018).

65

#### 66 **1b. Recent Volcanism in the Main Ethiopian Rift**

67 The Main Ethiopian Rift (MER) in the northernmost EARS (Fig 1), is a mature continental rift  
68 where strain is largely accommodated by magmatic intrusion and localised faulting within  
69 axial magmatic segments (Beutel et al. 2010; Casey et al. 2006; Ebinger and Casey 2001;  
70 Keranen et al. 2004). This pattern is especially well developed in the northern MER. Rifting  
71 initiated around 11 Ma in the northern MER (Wolfenden et al. 2004) and around 5-6 Ma  
72 (Bonini et al. 2005) or 8-10 Ma (WoldeGabriel et al. 1990) further south. Around 1.6-2 Ma,  
73 the distribution of activity narrowed and active faulting (Wonji Fault Belt, after Mohr 1962)  
74 and volcanism focussed within the rift floor, leading to the present-day structure (Boccaletti  
75 et al. 1998, 1999; Chernet et al. 1998; Corti 2009; Meyer et al. 1975). There is ongoing  
76 debate as to whether this shift in spatial distribution of volcano-tectonic activity results  
77 from a change in extension direction from orthogonal to oblique to the rift axis (e.g. Abebe  
78 et al. 2005; Boccaletti et al. 1998; Wolfenden et al. 2004), an increasing magmatic control  
79 over deformation (Buck 2006; Kendall et al. 2005) or continued oblique extension with pre-  
80 existing weaknesses (Corti 2008). The Wonji Fault Belt is an oblique intra-rift normal fault  
81 system which largely controls the spatial distribution of basaltic small eruptive centres (Fig  
82 1; Abebe et al. 2007; Keir et al. 2015; Mohr 1962; Rooney et al. 2011). In this study we focus  
83 on the recent (Late Pleistocene – Holocene) explosive volcanic activity in the central MER  
84 (~7-9 °N; ~38.5-40 °E): the regularly spaced silicic (caldera) complexes on the rift axis, and  
85 the fields of small eruptive centres of mostly mafic composition (Mohr and Wood 1976;  
86 Rooney et al. 2005, 2011; Fig 1). The main centres, from North to South, are Fentale, Kone,

87 Boset-Bericha, Gedemsa, Bora-Baricha, Aluto, Shala and Corbetti (Fig 1; see Supplementary  
88 Table 1 for a summary, with synonyms and unique GVP code). Two zones of small eruptive  
89 centres, considered to be Late Quaternary, occur off-axis in the Bishoftu (Debre Zeyt) and  
90 Butajira areas (Fig 1; Keir et al. 2015; Rooney et al. 2011).

91 The late Quaternary eruption histories of central MER volcanoes are poorly known.  
92 Improved knowledge of this volcanic history is however critical to assess contemporary  
93 volcanic hazards. Several MER volcanoes are sites of active geothermal energy development  
94 (Corbetti, Aluto), with others under exploration (Fentale, Tullu Moye), adding further  
95 incentive to understand potential volcanic hazards. Within the study area, three volcanic  
96 complexes are considered to have had historical eruptions of basaltic or rhyolitic lava:  
97 Fentale (13<sup>th</sup> century AD and/or ca. 1810 AD; Section 3h), Kone (ca. 1810 AD; Section 3g)  
98 and Tullu Moye (possibly late 18<sup>th</sup> century AD and/or ca. 1900 AD; Section 3d). The presence  
99 of volcanic ash layers in lacustrine sediment cores (Chalié and Gasse 2002; Martin-Jones et  
100 al. 2017), and pumice deposits on the edifices of Aluto (Hutchison et al. 2016b) and Corbetti  
101 (Rapprich et al. 2016) volcanoes suggest the frequent occurrence of explosive eruptions in  
102 the region.

103 We present new field observations and geochemical data on the youngest tephra  
104 deposits from the main silicic centres of Late Quaternary volcanic activity in the central  
105 MER. We review literature data to understand the nature of recent activity at each volcano,  
106 and evaluate contemporary volcanic hazards. The scope is deliberately broad and aimed at  
107 understanding eruption frequencies and magnitudes along the MER at first order. Our  
108 observations show that the most recent stages of post-caldera activity are variable in terms  
109 of eruption frequency, magnitude and style, despite the closely similar chemical  
110 compositions of the magmas and their tectonic environments.

111

## 112        **2. Field observations and geochemistry**

113        Fieldwork along the central MER was carried out in three campaigns between 2015 and  
114        2017. Interbedded sequences of tephra, soil and/or lacustrine deposits were logged and  
115        sampled in road cuts and gorges near Corbetti, Aluto, Bora-Baricha, Tullu Moye, Gedemsa,  
116        Boset-Bericha and Kone (Fig 1; localities in Supplementary Table 2), augmented with  
117        literature data from other MER volcanic centres.

118        Tephra samples were manually crushed, wet-sieved at 80  $\mu\text{m}$  to remove alteration  
119        products, and dried at 50 °C. Remaining ash shards were cold-mounted in pre-drilled EpoFix  
120        resin discs, ground down with SiC paper and further polished with diamond paste. We  
121        carried out glass major element analyses on polished carbon-coated surfaces by Electron  
122        Microprobe Analysis (EMPA) using a 4-spectrometer JEOL JXA-8600 Superprobe at the  
123        Research Laboratory for Archaeology and the History of Art, University of Oxford, with an  
124        accelerating voltage of 15 kV, a defocused beam of 10  $\mu\text{m}$ , and 6nA beam current. For highly  
125        vesicular samples with only small glassy surfaces, the beam size was reduced to 5  $\mu\text{m}$ , and  
126        beam current lowered to 4 nA. All elements were counted on-peak for 30 s (Si, Al, Fe, Ti,  
127        Mg, Ca, K), except for Na (12 s, and analysed first to minimise alkali loss), P (60 s), Mn and Cl  
128        (50 s). Off-peak background counting times were half the peak counting times. Data quality  
129        was continuously monitored by secondary glass standards analysed at the start, regularly  
130        during (at least after every 30 unknowns) and at the end of each analytical session. Average  
131        measured values on secondary standards generally fall within 2 standard deviations of  
132        published preferred values (Jochum et al. 2006, 2011). Error bars on the measurements of  
133        unknowns were calculated using the relative standard deviation of the measured values on

the standard that is closest in composition to the sample. Thirty individual points were attempted per sample. Analyses were carefully screened to evaluate the potential influence of hidden crystals or voids. Only analyses with totals above 92 wt% were retained, except for samples with analytical totals systematically below 95 wt%, in which case the threshold was lowered to 90 wt%. Analytical totals are generally relatively low, typically 94-95 wt%, which can be ascribed to secondary hydration upon alteration, the presence of dissolved volatiles or other minor elements not analysed for (H<sub>2</sub>O, F, Zr; e.g. Neave et al. 2012), and Fe<sub>2</sub>O<sub>3</sub> determined as FeO (Pearce et al. 2014). Representative results for each volcanic centre are presented in Table 1; the full dataset including secondary standards is available in Supplementary Tables 3a-b. For ease of comparison, data were normalised to 100 wt% on a volatile-free basis (i.e. also excluding Cl).

### **3. Results: a survey of post-caldera silicic volcanism along the Main Ethiopian Rift**

The new field observations, chemical data and Late Quaternary tephrostratigraphy for the silicic MER volcanoes are presented in Figures 2-13. For each volcanic complex, symbols are colour-coded across the figures showing geographic location, stratigraphy and chemistry. Summaries of the post-caldera eruptive history of each complex are presented in Table 2. Below we present our findings in the context of prior work at each volcano.

#### ***3a. Corbetti***

The Corbetti complex shows evidence for a three-stage volcanic history, first recognised by Di Paola (1971): effusive shield-building, caldera collapse and, following a hiatus, post-caldera pyroclastic activity. The caldera-forming eruption(s) at Corbetti emplaced at least one unit of welded ignimbrite and associated unwelded pyroclastic deposits (Di Paola 1971;

157 Rapprich et al. 2013; Hutchison et al. 2016c), dated to ca. 0.18 Ma (Table 1; Hutchison et al.  
158 2016c; WoldeGabriel et al. 1990).

159 At Corbetti, explosive and effusive eruptions of peralkaline rhyolite built the post-caldera  
160 edifices of Artu, Urji (or Wendo Koshe) and Chabbi (Fig 2). Artu is thought to predate both  
161 Urji and Chabbi, though no absolute chronological constraints exist (Rapprich et al. 2016).  
162 Deposits at the base of Chabbi date to ca. 20 ka (Table 1), suggesting that post-caldera  
163 activity at Corbetti has been ongoing since at least the latest Pleistocene.

164 Urji predominantly pumice fall and pyroclastic density current (PDC) deposits. Chabbi  
165 mainly comprises obsidian lava flows (Rapprich et al. 2016), many of which were preceded  
166 by a pyroclastic component (Mohr 1966; Di Paola 1972).. Rapprich et al. (2016) identify  
167 about a dozen events alternating between Urji and Chabbi. The most significant and  
168 widespread event is the Wendo Koshe Younger Pumice (WKYP), sourced from Urji, and  
169 dated at < 2.3 ka cal BP based on radiocarbon dating of underlying soil (Rapprich et al.  
170 2016). Martin-Jones et al. (2017) suggest that WKYP corresponds to a 1.3-1.9 ka cal BP  
171 tephra found in sediment cores in Lakes Tilo (Fig 1, 3) and Chamo (170 km SSW of Corbetti),  
172 which is surprisingly absent from Lake Hawassa. At least four of Chabbi's obsidian flows  
173 post-date WKYP (Rapprich et al. 2016), and the Lake Tilo sediment archive suggests at least  
174 one post-WKYP explosive eruption (Fig 3; Martin-Jones et al. 2017). According to Rapprich et  
175 al. (2016) the WKYP eruption started with small-scale PDC activity and extrusion of an  
176 obsidian lava flow, followed by a sustained explosive eruption that left a distinct pumice  
177 lapilli fall deposit with an eastward dispersal pattern, and that can be found well outside the  
178 caldera. We find no evidence for obsidian lithics in the WKYP fall deposit, and suggest the  
179 obsidian lava flow may post-date the fall deposit.

180 Glass from Corbetti pumice has a highly uniform pantelleritic composition (Fig 3), and  
181 based on major element chemistry alone, Corbetti deposits cannot easily be distinguished.  
182 Most of our new correlations between sections are constrained by lateral tracing in the field  
183 and depositional characteristics (e.g. lithic content, or characteristic bedding). Road sections  
184 within the Corbetti Caldera reveal at least two thick pumice fall deposits separated by  
185 multiple smaller-scale fall deposits (Fig 3). Pyroclastic sequences predominantly fall  
186 deposits, with light-grey aphyric pumice and populations of dense angular obsidian clasts.  
187 Obsidian clasts are virtually absent from the WKYP, which is easily identifiable in road  
188 sections N and E of the caldera. Some deposits show systematic rhythmic bedding at cm- to  
189 dm-scale, suggesting a pulsating nature of the eruption (Fig S1b; Section 3c). In some places,  
190 small-scale PDC deposits form m-scale stacks of low-angle cross-bedded and lenticular-  
191 bedded pumice and ash units (Fig S1a). From its stratigraphic position, lateral tracing and  
192 depositional characteristics we have identified WKYP in proximal and distal sections, and  
193 have updated the dispersal map (Fig 2). The upwind and southern dispersal is poorly  
194 constrained but volume estimates using the method of Pyle (1989) suggest a minimum  
195 deposit volume of 1.3 km<sup>3</sup>, with thicknesses of order of 0.5 m in the town of Shashemene  
196 (Fig 2). Another prominent and mostly rhythmically bedded pyroclastic deposit with  
197 obsidian clasts covers most of the eastern Urji flanks and underlies the WKYP, and is here  
198 called the Bedded Pumice. Both deposits are compositionally identical (Fig 3), but pumice  
199 textures and depositional features (massive vs. rhythmic bedding, presence vs. absence of  
200 obsidian) allow the deposits to be distinguished. Lateral tracing of thickness and maximum  
201 grain size patterns suggests the Bedded Pumice may be dispersed in a roughly circular  
202 pattern around Urji, with rhythmically-bedded packages several meters thick deposited  
203 within the caldera (Fig 2). The deposit thins rapidly to the north and south and this is

204 consistent with its rhythmically bedded nature resulting from pulsating behaviour gradually  
205 building a conical deposit. Other pyroclastic units exposed in sections within the caldera are  
206 of smaller scale (Fig 3).

207 Near the southern caldera rim, pyroclastic deposits predating the Bedded Pumice are  
208 exposed (e.g. section MER010, Fig 3-4b). The most recent unit exposed here is interpreted  
209 as Bedded Pumice because of its homogenous chemical composition as well as the  
210 occurrence of small-scale ash-rich PDC deposits covering a thin pumice fall unit, and which  
211 are also seen elsewhere. Two thick pumice lapilli breccia deposits underneath show slight  
212 compositional differences compared to the intra-caldera deposits, and can be correlated to  
213 selected ash layers from sediment cores from nearby lakes (Fig 3). A radiocarbon date on  
214 charcoal sampled from the soil underneath the oldest terrestrial deposit (MER010J; Fig 3-  
215 4b) is dated at  $7.75 \pm 0.04$  ka cal BP (Table 3). This unit chemically resembles (slightly  
216 reduced  $\text{Al}_2\text{O}_3$ ) a 6.3-8.7 ka cal BP tephra layer in Lake Tilo (TT-13), as well as the  
217 bottommost tephra in a Lake Hawassa core (AWT-7) which was dated at  $>7.4$  ka cal BP  
218 (Martin-Jones et al. 2017). A 5.7-6.2 ka cal BP tephra in the Lake Hawassa core shows  
219 slightly elevated  $\text{Al}_2\text{O}_3$  concentrations and can be correlated to a thick pumice fall deposit  
220 directly underlying the Bedded Pumice (Fig 3-4b).

221 From a composite stratigraphy of terrestrial sections we find at least 7 pyroclastic fall  
222 deposits separated by palaeosols in the last ca. 7-8 ky, 4 of which are correlated between  
223 multiple sections (e.g. MER001 and MER010; Fig 3). This is consistent with the frequency of  
224 occurrence of ash layers identified in the sediment cores from lakes Hawassa and Tilo  
225 (Martin-Jones et al. 2017; Fig 3). Sediment cores of Lake Garba Guracha, 167 km E of  
226 Corbetti in the eastern highlands (Fig 1), reportedly contain 4 tephra layers, ranging from 3

to 15 mm thick, in the last 14 kyrs (Tiercelin et al. 2008). Additional chemical data are required for verification, but the most likely source of these tephras is Corbetti. The combined terrestrial and lacustrine records thus suggest a first-order approximation of 1 explosive eruption per 700-1000 years (Martin-Jones et al. 2017; this study).

Small eruptive centres of unknown age occur immediately southeast of Corbetti, East of Lake Hawassa and North of Corbetti (red triangles on Fig 2). A rhyolitic tuff cone complex with its base ca. 40-50 m above the present-day northern shoreline of Lake Hawassa is partly overlapped by obsidian lava flows from Chabbi and surrounded by lacustrine and alluvial sediments (Rapprich et al. 2013; Fig 2). The morphology of the complex, together with the observed chaotic and heterolithic nature of its proximal deposits, mostly emplaced by PDCs (Ben Clarke, pers. comm.), suggests it may have a phreatomagmatic origin. This would be consistent with its location near the lake (e.g. Belousov and Belousova 2001; Poppe et al. 2016) although more detailed facies analyses are needed to confirm this (e.g. White and Valentine 2016). The cones east of Lake Hawassa, including one near the present-day shoreline in the city of Hawassa (Fig 2), are basaltic, and some are interpreted to have a phreatomagmatic origin (Rapprich et al. 2013). Basaltic scoria cones North of Corbetti seem to have erupted mostly along faults continuing further North to Shala Caldera (Fig 2, 5).

### **3b. Shala Caldera**

The pre-caldera geology of the Shala caldera which contains the 250 m deep Lake Shala (Di Paola 1972) comprises deposits of rhyolitic and trachytic effusive and explosive eruptions, including extensive ignimbrites, pumice flow and pumice fall deposits exposed in the caldera



walls. Green-grey welded and unwelded ignimbrite deposits associated with the caldera-forming eruption(s) at Shala are dated at  $240 \pm 30$  ka (bulk K-Ar; Mohr et al. 1980).

Post-caldera activity at Shala appears limited, and mostly concentrated at the Tullu Fike pumice dome complex (Fig 2). This lies outside the caldera, and is built on an apron of pumice that is 40 m thick on the northern caldera rim (Mohr et al. 1980; Fig 2). The volume of the Tullu Fike complex is ca.  $3 \text{ km}^3$  DRE, an order of magnitude less than the cumulative post-caldera eruptive volumes of neighbouring Corbetti or Aluto (Hutchison et al. 2016c). The age of this post-caldera activity is not known, but Tullu Fike may be the source of pumice deposits interbedded with Late Quaternary lacustrine sediments in the Shala caldera walls (Mohr et al. 1980). It is not known whether any eruptive centres exist within the submerged caldera.

A few manifestations of basaltic (post-caldera?) volcanism occur in the form of isolated scoria cones in the north and a maar complex and scoria cones in the south (Mohr et al. 1980; Galo Salen unit of Trua et al. 1999; Fig 2). Some of these basaltic centres may be associated with Wonji faults cross-cutting the caldera and the area south of it, and which are in some cases also associated with hot springs (Baumann et al. 1975; Hunt et al. 2017).

### **3c. Aluto**

The long-term magmatic evolution of the Aluto volcanic complex involves a trachytic shield-building phase, culminating in one or two caldera-forming eruptions at ca. 300-320 ka (Hutchison et al. 2016b-c). In at least the last 60 kyrs, post-caldera activity has largely filled in, and almost concealed, the caldera, with the eruption and construction of pumice cones and obsidian domes on the edifice (Fig 6; Hutchison et al. 2015, 2016b).

272 To the west and south-west of the complex, Late Pleistocene and Holocene pyroclastic  
273 deposits occur interbedded with lacustrine deposits related to Pleistocene and Holocene  
274 lake level high stands of the Ziway-Shala basin (Benvenuti et al. 2002, 2013; Gasse and  
275 Street 1978; Le Turdu et al. 1999). Sediment cores from nearby Lakes Abijata (Abiyata) and  
276 Langano, taken 24 km SW and 14 km S of Aluto, respectively (Fig 1), suggest the occurrence  
277 of up to 25 distinct ash horizons in the last 12 kyrs (Chalié and Gasse, 2002; Gibert et al.  
278 1999, 2002). Aluto is the most likely source for most of these tephras, suggesting a first-  
279 order recurrence of 2-3 explosive eruptions per millennium at Aluto at least since the latest  
280 Pleistocene.

281 Our field observations and sampling at Aluto focused on the young pyroclastic units on  
282 the edifice (Fig S1c-d), and those interbedded with lacustrine sediments exposed in deep  
283 river gorges mainly to the west of the complex (Fig 5, 4d). These latter sections expose tens  
284 of meters thick alternations of up to 20 individual pyroclastic deposits with lacustrine  
285 deposits (diatomites) and/or palaeosols (Fig 4c). Where they are interbedded with lacustrine  
286 deposits, most of these pyroclastic deposits are dominantly clast-supported and relatively  
287 well-sorted pumice lapilli breccias at the bottom, with the appearance of a pumice fall  
288 deposit. They typically transgress upwards into a more poorly-sorted facies with more fine  
289 ash (and possibly diatomite) in the matrix (Fig 4d). Parallel bedding is common, though  
290 some units also display undulated and low-angle cross bedding in the fines-dominated parts.  
291 Occasionally matrix-supported deposits of laterally varying thickness (up to 1-2 m) and with  
292 scattered subrounded pumice clasts occur, interpreted as PDC deposits. Most deposits are  
293 interpreted to be fallout that settled through water, with their top, ash-rich parts resulting  
294 from the continued arrival of pyroclastic material deposited in the lake's catchment and  
295 remobilised as lahars (e.g. Manville et al. 2009). At ca. 8-10 km distance from the centre of

296 Aluto, the lowermost clast-supported parts of the deposits span thicknesses from a few cm  
297 to a few tens of dm, which are typically matched by the thickness of the upper matrix-  
298 supported parts.

299 Glass major element analyses of pumice lapilli and ash samples both from the main  
300 edifice and individual pyroclastic units interbedded with soils or lacustrine deposits (section  
301 A01, Fig 5) from a river gully section to the NW, shows that most pumice deposits have  
302 distinct pantelleritic compositions (Fig 6; colour-coded sample localities on Fig 5). The  
303 topmost, Qup, was previously tentatively correlated to the abundant young-looking pumice  
304 deposits occurring under the topsoil on much of the Aluto edifice (Hutchison et al. 2016b).  
305 Its distinct chemical composition however only correlates to a limited number of locations  
306 sampled across the edifice and to the west (grey dots on Fig 5, blue ones indicate samples  
307 with Qup composition; Fig 6). Rather than being the product of a single Plinian-style  
308 eruption, we infer that the previously mapped Qup unit comprises multiple pumice lapilli  
309 fall deposits sourced from different vents on the edifice. These deposits are often  
310 rhythmically bedded at a dm-scale (Fig S1d), which, together with the variety in chemical  
311 composition, is consistent with the presence of multiple pumice cones built up along the  
312 trace of the caldera ring fracture (Hutchison et al. 2015). Such pumice cones would locally  
313 have deposited thick accumulations of pumice lapilli and localised PDC deposits that  
314 overlapped, but were not widely dispersed. This is consistent with the presence of multiple  
315 moderate-scale pyroclastic deposits interbedded with the lacustrine sediments West of  
316 Aluto (Fig 4c-d, 5, S1c-d). We infer that the “true” Qup deposit, i.e. the youngest unit in  
317 section A01, and in section MER060 (Fig 5, S1c) was likely sourced from a pumice cone to  
318 the NW of the inferred caldera, and which has a prominent ca. 300 m diameter crater  
319 (Hutchison et al. 2016b). Four units underlying Qup in A01 are locally correlated in the

lacustrine and terrestrial sections to the NW of the edifice (Fig 5). Radiocarbon dating on shells incorporated in these pyroclastic and lacustrine deposits suggests the top three larger deposits, A9 (corresponding to Qup), A8 and A7 (Fig 5), to have been emplaced within the last 7,300 years (McNamara et al., unpublished data). A full integration of these sections with lake sediment cores will further improve our understanding of the frequency and magnitude of explosive eruptions at Aluto.

One sample of a 15 cm thick pumice layer with an ash matrix, taken NE of Lake Langanò (pink dot on Fig 5) resembles some Corbetti glass compositions (Fig 3, 6). This pumice layer lies between two soil-and-breccia deposits, similar to those interpreted by Benvenuti et al. (2013) as early Holocene shore deposits. Gastropod shells from immediately beneath the pyroclastic unit were dated at  $11.97 \pm 0.09$  ka cal BP (Table 3), and we suggest that this pyroclastic unit may form an early Holocene regional marker horizon from Corbetti.

Numerous scoria cones of basaltic composition have erupted along faults associated with the Wonji Fault Belt which obliquely cross-cuts the rift floor to the East of Aluto but which do not have an obvious physical connection to the complex (Fig 1, 5). With the exception of one trachyandesitic scoria cone to the NW of the complex (TAC in Fig 5) and potentially mafic components in a few (tuff) cones (all of unknown age) in the vicinity of Lake Ziway (TC in Fig 5), no clear manifestation of post-caldera mafic or intermediate volcanism is known at Aluto (Hutchison et al. 2016b; Di Paola 1972).

### **3d. Bora-Baricha and Tullu Moye**

The low-relief complexes of Bora-Baricha and Tullu Moye, between lakes Ziway and Koka (Fig 1, 7) are poorly accessible and the least studied MER volcanoes. Welded pantelleritic

ignimbrites outcrop in the heavily faulted SE of the complex (Trua et al 1999) and have reported ages ranging from 115 ka to 1.8 Ma (fission track and K-Ar; Bigazzi et al. 1993). Remnants of caldera walls may largely be concealed by younger eruptive products. The Bora edifice is highly dissected, whereas Baricha and the Tullu Moye complex both have abundant obsidian lava flows and domes with limited soil cover, as well as hydrothermal manifestations (Fig 7; Admassu Bahiru 2007; Mengistu Darge et al. 2017).

Exploration on western and eastern sides of the complex reveals abundant silicic pyroclastic material in the form of (sometimes crudely parallel-bedded) pumice and ash fall deposits and subordinate PDC deposits. Near Baricha we find an accumulation of > 7 pumice lapilli breccia deposits alternating with poorly-developed palaeosols (section MER147; Fig 7, 8a-b). These deposits are typically characterised by a light grey dominant pumice component and a small proportion of darker grey vesicular pumice and angular obsidian chips. The pumice is a sanidine-phyric pantellerite (Fig 8c). A nearby gully exposes at least 6 more pyroclastic deposits underneath. The age of these deposits is unconstrained due to the lack of dateable material (e.g. charcoal); however the fresh appearance of the pumice and limited soil cover is consistent with a Late Quaternary age.

To the southeast of the complex, section MER150 reveals a stack of > 5 pyroclastic fall and PDC deposits, each unit multiple meters thick, and alternating with poorly-developed soils and reworked yellow ash horizons (Fig 7, 8a-b). The pumice lapilli are light grey and very phenocryst-poor to aphyric, and the deposits generally contain a few % of obsidian lithics as well as some (hydrothermally) altered lithic clasts. Several meters of subparallel cm-scale bedded poorly-sorted deposits of coarse ash, pumice and obsidian show subtle

366 thickness variations and minor cross-bedding in the individual beds, interpreted as dilute  
367 PDC deposits. Pumice in all units is pantelleritic, but the top unit (MER150C) is distinctive  
368 and may form a fractionation trend towards the Tullu Moye comendites (MER152; Fig 7, 8c).  
369 We suspect that the low-relief ridges and domes to the east of Bora, including the Oda  
370 crater (Fig 7), were the source of most of the deposits of MER150.

371 Pyroclastic deposits near Tullu Moye are typically poorly-sorted pumice lapilli and bomb  
372 breccia deposits, with angular blocks of obsidian (MER152; Fig 8b). The light grey  
373 phenocryst-poor pumice has a comenditic glass composition (Fig 8c) and often appears  
374 highly altered, with abundant secondary mineralisation. This is consistent with the  
375 persistent hydrothermal activity in the region (Mengistu Darge et al. 2017).

376 Poorly-vegetated obsidian lava flows near Tullu Moye (Di Paola 1972; Gouin 1979; Global  
377 Volcanism Program, <http://volcano.si.edu>) occur along fissures with the same strike as faults  
378 cutting through basaltic scoria cones further south as well as north towards Gedemsa (Fig  
379 7). The youngest (least vegetated) of these obsidian flows erupted from two NNE-SSW  
380 aligned vents and formed two highly fractured > 5 m thick lava lobes; one elongate and ca.  
381 2.7 km long by 1.6 km wide (also known as “Giano”, Bizouard and Di Paola 1978), and one  
382 circular lobe ca. 1 km in diameter (darkest green lobes on Fig 7). The brecciated lava is dark  
383 grey to black and phenocryst-poor, with individual blocks showing decimetre-scale vesicular  
384 banding. Eyewitness accounts mentioned in Gouin (1979) suggest the eruption took place  
385 around 1900 AD and may have been associated with an ash fall. Bizouard and Di Paola  
386 (1978) attribute this same lava flow (“Giano”) to an eruption “only two centuries ago”, i.e.  
387 late 18<sup>th</sup> century AD (Siebert et al. 2010; Global Volcanism Program: <http://volcano.si.edu>).  
388 It is possible that both sources in fact refer to the same, poorly dated eruption. Another

389 young but slightly more vegetated obsidian flow occurs ca. 5 km further SSW (brightest  
390 green lobe on Fig 7) and is consistent with two recent eruptions happening in the Tullu  
391 Moye area.

392

### 393 **3e. Gedemsa**

394 Gedemsa is a ca. 8 km diameter and well-expressed caldera cut by the NNE-SSW trending  
395 Wonji Fault Belt along its eastern side (Fig 7). Pre-caldera products exposed on the outer  
396 flanks of the complex mostly consist of rhyolitic lava flows and domes, and pumice fall  
397 deposits (Thrall 1973; Peccerillo et al. 2003).

398 Light to dark grey pumice breccia deposits up to 40 m thick are described to the W of the  
399 caldera (Thrall 1973). In the north, these coarse pumice deposits alternate at a metre-scale  
400 with a few tens of cm thick packages of low-angle cross-bedded pyroclastic deposits from  
401 dilute PDCs (Fig 9a). They are overlain by a lower dark and dense, and an upper green and  
402 columnar-jointed welded ignimbrite (Thrall 1973). The green welded ignimbrite is overlain  
403 by pumice breccia deposits up to 20 m thick (Thrall 1973). The ignimbrites are typically  
404 associated to one or more caldera-forming events (Peccerillo et al. 2003), but given the  
405 volume of the underlying sequence of major unconsolidated pyroclastic deposits, including  
406 coarse pumice lapilli breccias, we suspect these latter deposits may also be related to the  
407 formation of the caldera. K-Ar dating on crystal separates of unidentified pre- and post-  
408 caldera products constrains the formation of the caldera to within  $265 \pm 0.02$  and  $319 \pm 0.02$   
409 ka (Peccerillo et al. 2003). Morton et al. (1979) however present a bulk K-Ar age of  $0.85 \pm$   
410  $0.07$  Ma for a green welded tuff on the N rim of the Gedemsa caldera.

411 Light to dark grey pumice breccia banked up against green welded ignimbrites in the  
412 southern caldera wall (MER076A/B; Fig 7) correspond chemically to a grey pumice lapilli  
413 breccia deposit on the eastern flank of the complex (MER094A; Fig 7, 9d-e). Another poorly-  
414 sorted dark grey pumice lapilli fall deposit underlies welded ignimbrites in the NE caldera  
415 rim and on the NE flank (MER084A; Fig 7, 9a), and corresponds chemically to pyroclastic  
416 deposits exposed in a river gully to the east (MER077A/B; Fig 7, 9d-e). Here, crudely bedded  
417 dark grey fine pumice lapilli breccia interpreted as a fall deposit, is overlain by a poorly-  
418 sorted matrix-supported deposit with dispersed clasts of light grey fibrous pumice lapilli.  
419 This deposit gradually transgresses upwards into a welded facies, and is interpreted as a  
420 PDC deposit. Both deposits are separated by an ash- and lithic-rich soil suggesting a  
421 temporal hiatus. The similar chemical composition and widespread nature of the deposits  
422 however is consistent with both events being related to caldera-forming eruptions which  
423 were relatively closely spaced in time in the Late Quaternary.

424 Three intra-caldera coalesced domes, Kelo, Dima and Kore, are aligned WNW-ESE (Fig 7;  
425 Acocella et al. 2002) and mostly comprise poorly-sorted pumice lapilli and bomb breccias,  
426 interpreted as proximal fall deposits from the domes (Fig 9b). Kore, the easternmost centre  
427 on this alignment, has a prominent ca. 600 m diameter summit crater. Interbedded locally  
428 welded facies and obsidian lavas also occur within the deposits of these domes (Thrall 1973;  
429 Giordano et al. 2014). Several low-relief dome-shaped constructs are also identified in the  
430 northern and southern half of the caldera (Fig 7) and presumably also represent post-  
431 caldera centres of activity, though their interpretation as an eruptive volcanic feature is  
432 ambiguous.



433 Our sampling revealed at least 6 different pumice lapilli fall deposits that are  
434 geochemically distinct from the caldera-forming pyroclastic deposits (Fig 9d-e). Three of  
435 these were sampled from the proximal deposits of the intra-caldera Kore, Dima and Kelo  
436 edifices and are all pantelleritic in composition (Post-caldera cluster in Fig 9d-e). Three more  
437 geochemically unique pumice lapilli fall deposits from sections near the NE rim and E of the  
438 caldera presumably relate to additional post-caldera silicic activity, the source vents of  
439 which are however not constrained (Fig 7, 9d-e). Thicknesses of these deposits in these  
440 localities are of order of a few tens of cm.

441 Near the NE caldera rim, subparallel and low-angle cross-bedded poorly-sorted deposits  
442 with up to 10-15 cm clasts of scoria, basaltic lava and obsidian in an ash-rich matrix occur  
443 stratigraphically above the post-caldera pumice fall deposits (MER081A; Fig 9c-e). They are  
444 interpreted as deposits of dilute PDCs, possibly phreatomagmatic in origin. Peccerillo et al.  
445 (2003) relate them to the basaltic volcanism along the Wonji Fault Belt, with evidence for  
446 entrapment of intrusive silicic magmas from the crystallising post-caldera Gedemsa  
447 reservoir. The exact age of this activity is unknown.

448 Basaltic scoria cones (Peccerillo et al. 2003; Rooney et al. 2007) occur immediately NE, E  
449 and S(E) of the complex, aligned with the Wonji Faults (Fig 7). These cones lack silicic  
450 enclaves (Peccerillo et al. 2003) and are considered structurally unrelated to Gedemsa.

451 Immediately NW and SW of Gedemsa caldera, Thrall (1973) describes pantelleritic lava  
452 domes and local pumice deposits cut by morphologically young faults (Fig 7). It is not known  
453 whether these belong to the pre- or post-caldera stage of volcanism of the Gedemsa  
454 complex. The same faults control the location of hydrothermal springs a few km further  
455 north (Abdulkadir and Eritro 2017).

456

457 **3f. Boset**

458 Midway between Gedemsa and Boset lies the Melkassa (also known as Sodore) field of ca.  
459 30 scoria cones around the largely eroded ca. 5 km diameter Boku caldera (Fig 10). An  
460 obsidian lava flow from this caldera was dated by Morton et al. (1979) at  $0.83 \pm 0.02$  Ma  
461 (bulk K-Ar). The Melkassa scoria cones and associated lava flows are morphologically young  
462 and suspected to be of Late Pleistocene – Holocene age (Boccaletti et al. 1998, 1999; Siebert  
463 et al. 2010).

464 The Boset volcanic complex comprises two adjoining stratovolcanoes that grew along a  
465 NNE-SSE trending lineament parallel to the Wonji Fault Belt. The southern and largest of the  
466 two volcanoes is called Boset-Gudda (also “Tiliki Boset” or “Great Boset”), the northern one  
467 Boset-Bericha (also “Tinishi Boset” or “Little Boset”; Fig 10). Gudda has a 2.5 km arcuate  
468 ridge on its NW slope, which may represent the remnant of a largely infilled caldera (Di  
469 Paola 1972). In a study of the long-term evolution of the Boset volcanic complex constrained  
470 by absolute lava flow Ar-Ar chronology, Siegburg et al. (2018) constrain the caldera  
471 formation to after  $119.8 \pm 6.1$  ka. We identified a >3.5 m thick stack of altered coarse  
472 pumice lapilli breccia and finely parallel and cross-bedded ash and small pumice lapilli  
473 deposits of dilute PDCs interbedded with palaeosols on the SE lower flank of the complex,  
474 and underneath a lava flow (outcrop MER120, Fig 10). These deposits are pantelleritic in  
475 composition, but different from the more recent pyroclastic units to the West (Fig 11). We  
476 infer the former to relate to the “ashy and pumiceous falls” described by Ronga et al. (2010)  
477 for the late-stage pre-caldera or syn-caldera activity. More dedicated studies are needed to

infer where these deposits sit in the long-term stratigraphy of the complex, and whether or not they relate to caldera-forming events.

The two central edifices of the complex mainly comprise thick trachytic and peralkaline rhyolite lava flows with associated pyroclastic deposits (Macdonald et al. 2012). These silicic lava flows have run-out distances of up to 11 km (Siegburg et al. 2018) and are often sourced from breached cones. The summit of Gudda contains a handful of NE-SW aligned small craters, up to 200-300 m diameter (blue stars on Fig 10), some with associated short obsidian lava flows (Di Paola 1972) of Holocene age ( $3.3 \pm 2.4$  ka, Ar-Ar on feldspar separates, Phase O of Siegburg et al. 2018).

Road and dry river gully sections on the Western lower flank of Boset (Fig 10) expose alternations of palaeosols and up to 6 individual pyroclastic deposits, interpreted as fall deposits, one of which is scoriaceous (Fig 11). We propose section MER108 (Fig 10-11) as the type section for the young tephrostratigraphy at Boset.

The most recent deposit is also the most voluminous and widespread, and is here called the “Boset Pumice”. It comprises well-sorted pumice lapilli breccia deposits with a minor fraction of small obsidian chips, and is interpreted as a Plinian-style fall deposit. Pumice lapilli are white to light grey, very crystal-poor and have a uniform pantelleritic glass composition (Fig 11). The deposits are crudely parallel-bedded in the most proximal outcrops, where they reach thicknesses of more than 3 m and are commercially exploited. The westward distribution suggests a primary depositional thickness of order of 20 cm in the city of Adama (Fig 10). The northern and eastern (upwind) dispersal are poorly constrained but visits to outcrops along the lower Boset flanks suggest absence of the Boset Pumice deposit in these areas. A first-order approximate volume calculation using the method of

501 Pyle (1989) suggests a minimum deposit volume of 0.5 km<sup>3</sup>, corresponding to a sub-Plinian  
502 eruption. From the general dispersal pattern we infer that the source vent was located on  
503 the Gudda edifice, and it may correspond to one of the craters identified as part of the  
504 youngest, Late Holocene, phase of activity at Gudda by Siegburg et al. (2018).

505 Recent basaltic trachyandesitic (mugearitic) lava flows were erupted from the saddle  
506 between the rhyolitic Gudda and Bericha edifices (Di Paola 1972; Brotzu et al 1974; Siegburg  
507 et al. 2018). Their whole rock composition (Brotzu et al. 1974) is very similar to that of a thin  
508 scoria fall deposit which is traceable over more than 10 km (scoria unit #2, found in MER095  
509 and in type section MER108; Fig 10-11) and we therefore suspect the latter corresponds to  
510 an explosive phase of these mostly effusive eruptions. This is also consistent with the  
511 Holocene age ( $4.2 \pm 3.2$  ka, Ar-Ar dating on feldspar separates) constrained for one of the  
512 lava flows (Fig 10; Siegburg et al. 2018). Several scoria cones of basaltic composition occur  
513 along the NE lower flanks of the complex, and are mostly aligned NE-SW (Fig 10).  
514 Geochemical analysis on a selection of these scoria cones shows them to have similar  
515 basaltic compositions (MER109A, MER116A and MER117A; Fig 10), distinct from our scoria  
516 #2 (Fig 11). Other scoria cones occur to the SW of the complex, and are associated with the  
517 Melkassa volcanic field (Fig 10).

518 The basaltic trachyandesite scoria fall deposit directly overlies a lithic-poor and crystal-  
519 poor pumice fall deposit, and is intermixed in one outcrop. Both eruptions may therefore  
520 have occurred almost simultaneously. The second pumice lapilli fall (#3 in Fig 11) is  
521 markedly thinner and less widespread than the Boset Pumice, but has a similar pantelleritic  
522 composition, and is therefore likely to be sourced from Gudda (Siegburg et al. 2018). A third  
523 pantelleritic pumice fall deposit occurs underneath pumice #3. It is normally graded and

finer grained than the Boset Pumice (pumice unit #4; Fig 11). Finally, at the base of the type section MER108 (Fig 10) is a lithic-poor white pumice lapilli deposit with a distinct comenditic glass composition (Fig 11). In one section NW of the complex (MER115, Fig 10), another comenditic pumice lapilli fall deposit occurs underneath pumice #5, separated by a soil. Comenditic lava flows are only known from the Bericha edifice of the Boset complex (Siegburg et al. 2018), so we infer these lowermost comenditic pumice fall deposits to have derived from Bericha. The most recent lava flows at Bericha date to the latest Pleistocene and Holocene (Siegburg et al. 2018) and some may be associated with the comenditic pumice fall deposits.

### **3g. Kone**

The Kone (Gariboldi in older literature) volcanic complex comprises at least three well-expressed nested calderas (Fig 12): the oldest, partially obscured Birenti Caldera which may include two nested collapse features (Cole 1969), the younger Kone Caldera and the Korke embayment (Rampey et al. 2010).

Pre-caldera activity at Birenti and Kone mostly comprises trachyte and alkali rhyolite lava flows and domes exposed in the caldera walls (Rampey et al. 2010). The caldera-forming eruptions emplaced up to several meters or tens of meters of unwelded pumice fall deposits interbedded with welded ignimbrites, typically green in colour and with varying proportions of fiamme and accidental lithics (Rampey et al. 2010). We sampled a sequence of unwelded, coarse grey pumice lapilli and bomb breccia deposits along the road between the Kone and Birenti calderas (Fig 12). We interpret these pyroclastic fall deposits as related to some of

the major events described by Rampey et al. (2010). Major element glass chemistry suggests three distinct comenditic to pantelleritic compositions (Fig 13). We infer the comenditic pumice, sampled from three localities along the N rim of the Korke embayment, to be associated with the Kone caldera forming event(s) (unit Qpk, after Rampey et al. 2010). The pantelleritic pumice may represent other units within the Kone pyroclastic sequence, or other phases from the Kone Caldera Complex. MER141A (yellow symbols in Fig 12-13) may correspond to a non-welded pyroclastic facies of the Birenti caldera-forming events (units Qub or Qim, Rampey et al. 2010). MER130A (blue symbols in Fig 12-13), a poorly-sorted, >2.5 m thick grey coarse pumice lapilli and bomb breccia deposit, may correspond to the pyroclastic deposits associated with a post-caldera rhyolitic dome on the southern Kone caldera wall (units Qrd and Qpd, Rampey et al. 2010).

The age and detailed stratigraphy of these events remains poorly constrained, and it is unclear which eruption formed the Korke embayment (Rampey et al. 2010). Williams et al. (2004) show a schematic section near the SE margin of the Kone caldera, where a welded ignimbrite and overlying ash (flow?) and pumice fall deposits lie beneath a Middle Stone Age palaeosol (> 200 ka; Basell 2008; Williams et al. 2004). Without additional spatial and geochemical data it is not possible to assign a correlation with any of the pyroclastic deposits described by Rampey et al. (2010).

In a study of Middle Stone Age obsidian tool provenance, potential obsidian source rocks sampled near the NE rim of the Kone caldera were Ar-Ar-dated at  $391 \pm 2$  and  $395 \pm 6$  ka (Vogel et al. 2006). Glass geochemical data on these same black to deep green obsidian source rocks (Negash et al. 2007) are closely similar to MER141A (yellow symbols in Fig 12-13), and may put a temporal constraint on the formation of these deposits.

570 Rampey et al. (2010) describe the few post-caldera silicic lava flows and domes which  
571 erupted along the southern and northern Kone caldera rims, and along NE-SW oriented  
572 faults north of the complex. Sparse pyroclastic deposits are also associated with the caldera  
573 ring fault (and may correspond to MER130A, blue symbols in Fig 12-13, see above), but the  
574 age of these eruptions is unconstrained, and it is unclear whether they are representative of  
575 the contemporary volcanism at the Kone Caldera complex. In our reconnaissance visit we  
576 did not find any evidence for fresh-looking loose pyroclastic deposits of silicic composition.

577 Recent basaltic lava flows erupted from NE-SW aligned scoria cones on the hinge  
578 between the Kone and Korke calderas, filling both caldera floors (Acocella et al. 2002). The  
579 most recent of these events may have occurred historically, with many secondary sources  
580 suggesting an eruption date of ca. 1810-1830 AD (e.g. Buxton 1949; Cole 1969), originally  
581 derived from the accounts of Harris (1844). In April 1842, Harris visited the “crater of Saboo”  
582 (Sabober, S of Fentale; Fig 12), which was “said to have been in full activity in the time of  
583 Sahela Selassie’s grandsire” (Harris 1844, p. 255). Selassie’s grandfather, Asfaw Wossen, was  
584 ruler of Shoa from 1774-1808 (Keynes 2007). Harris also visited Kone, which he describes as  
585 “the crater of Winzegoor”, and where he noted that the fresh lavas were still “jet black”,  
586 and that two “bare truncated cones” erupted “some thirty years previously” remained dark  
587 and cindery. One reading of Harris’ accounts is that there was an episode of mafic rift-floor  
588 volcanism extending between Kone and Fentale, similar to the Dabbahu – Manda Hararo  
589 rifting episode from 2005-2010 (e.g. Ferguson et al. 2010), and that this had a peak in the  
590 later parts of Asfaw Wossen’s reign, perhaps ca. 1800-1808. Other morphologically fresh  
591 and poorly vegetated, blocky basaltic lava flows occur to the N and NE of the caldera  
592 complex, most notably to the N of a large scoria cone, Beru (Fig 13). Our glass geochemical  
593 analyses confirm the basaltic composition for these recent scoria cones (Fig 12-13).

594

595 **3h. Fentale**

596 Fentale is the northernmost MER volcano, at the junction with the Afar depression, and  
597 hosts a ca. 2.5 by 4 km diameter summit caldera elongated NNW-SSE (Fig 12). The green  
598 welded ash-flow tuff of Fentale that was emplaced by the caldera-forming eruption is dated  
599 at  $168 \pm 38$  ka by fission track dating on the glass (Williams et al. 2004). Based on the  
600 chemical composition of different flow units identified within the ash-flow tuff, Gibson  
601 (1974) suggested the related eruption emptied a chemically zoned magma chamber with a  
602 trachytic base and rhyolitic top. On the southern flank, the welded tuff deposit has  
603 distinctive blisters, sometimes up to 100 m in diameter, presumably formed by degassing of  
604 large coalesced gas pockets within the newly emplaced deposit (Gibson 1970).

605 Post-caldera eruptions of obsidian and rhyolite lava flows were sourced from NNW-SSE  
606 aligned vents and fissures within the caldera (Acocella et al. 2002), as well as on the NE, E,  
607 SE and W flanks of the volcano (Williams et al. 2004; Gibson 1974). The morphologically  
608 youngest and most poorly vegetated obsidian flow was erupted from a vent within the  
609 caldera. Some post-caldera eruptions emplacing obsidian lava flows possibly also had an  
610 explosive phase, as evident from fresh superficial pumice lapilli scattered around the lower  
611 slopes of Fentale. There is however no evidence for significant silicic explosive volcanism  
612 emplacing widespread pumice fall deposits in the post-caldera stage at Fentale.

613 Basaltic activity near Fentale occurs immediately South of the edifice. A basaltic tuff  
614 cone, Tinish Sabober (Williams et al. 2004; Fig 12) is covered on its flanks with a veneer of  
615 welded tuff from the caldera-forming eruption, hence pre-dates it (Gibson 1967, 1974).  
616 Much more recent basaltic activity has occurred in the same region with the emission of



lava flows from fissures and small cones aligned NE-SW with the centre of the tuff cone (Williams et al. 2004). Local oral tradition reported by Harris (1844, p255) suggests activity during the reign of Asfaw Wossen, who died in 1808 (Keynes 2007; Section 3g). The fresh and almost non-vegetated nature of the Fentale basaltic lava flows, similar to those at the Kone caldera complex, does suggest they may have erupted historically.

A poorly documented “13<sup>th</sup> century” eruption of Fentale is reported in Newhall and Dzurisin (1988), after Azais and Chambord (1931), who record an account by a priest mentioning the destruction of a church and town near present-day Lake Metehara (also known as Lake Beseka, Fig 12). It is unclear whether this event could actually relate to the 19<sup>th</sup> century lava flows, given their geographic location close to the lake, or whether it represents an eruption from a vent elsewhere on the edifice.

### ***3i. Off-axis volcanism***

Our evaluation of recent volcanism in the MER is focussed on the on-axis volcanic centres within the MER, which are generally assumed to be the locus of most of the present-day volcanic and tectonic activity (e.g. Corti 2009; Keir et al. 2015). Off-axis volcanism occurs as small eruptive centres of mainly basaltic composition in the Bishoftu (Debre Zeyt) and Butajira volcanic fields on the Western rift shoulder (Fig 1; Rooney et al. 2005, 2011). In the Bishoftu area several phreatomagmatic vents (maars) exist and these comprise pumiceous tuff deposits (Emilia et al. 1977). This off-axis volcanism is generally assumed to be Late Quaternary in age because of its morphologically young appearance, though absolute chronologies or modern evaluations of their potential future hazards are lacking. To the

southern end of the Bishoftu area, the large silicic volcano of Ziquala (Zuquala) dominates the landscape, and has a prominent summit crater hosting a lake. Trachytic lavas from the base, flank and rim of the volcano were dated (K-Ar on feldspar separates) between  $0.85 \pm 0.05$  and  $1.28 \pm 0.15$  Ma (Morton et al. 1979) but its youngest eruptive products have not been studied.

## **4. Discussion**

### ***4a. Diversity in style and rate of silicic volcanism along the MER***

The timing of caldera-forming eruptions and initiation of post-caldera activity along the MER is still relatively poorly constrained, with the exception of recently re-evaluated ages at Aluto and Corbetti using high-precision sanidine Ar-Ar dating as opposed to bulk K-Ar dating (Hutchison et al. 2016c). In this study we focus mainly on the youngest post-caldera activity at each MER centre as constrained by field observations. Post-caldera Late Quaternary activity along the MER is dominated by effusive and/or explosive eruptions of peralkaline rhyolitic magmas, generating obsidian flows and domes and pumice cones within the old calderas, at all centres except Kone (Table 2).

Corbetti and Aluto have both been highly active in the Late Quaternary, as evidenced by the presence of numerous volcanic ash layers in lacustrine sediment cores spanning the last 12,000 years (Chalié and Gasse 2002; Martin-Jones et al. 2017), and multiple pumice fall deposits on their edifices. Deposits of these explosive eruptions are moderately widespread, with some suggesting up to sub-Plinian scale magnitudes (typically VEI 3-4, which would correspond to deposit volumes of order of  $0.1 \text{ km}^3$ ; Newhall and Self 1982; Pyle 2015, 2016). The best documented and youngest deposit in our record from Aluto presented here, Qup,

663 is almost 3 meters thick near its presumed source vent, but rapidly thins away to a few tens  
664 of cm or even less within 5 km distance both to the W and E (Fig 5). Deposits of similar scale  
665 are also found at Tullu Moye and Boset-Bericha. At Gedemsa and possibly also at Tullu Fike  
666 near the Shala Caldera, we find more localised coarse pumice bomb breccia deposits  
667 representing post-caldera stage explosive activity (Table 2).

668 The metre- to decimetre-thick proximal pyroclastic fall deposits found at Corbetti, Bora-  
669 Baricha and Boset-Bericha are consistent with larger, VEI 4-5 eruptions generating deposit  
670 volumes of ca. 1 km<sup>3</sup> (Newhall and Self 1982; Pyle 2015, 2016). At Corbetti there is evidence  
671 for two such Holocene events, in addition to multiple smaller-scale explosive eruptions (Fig  
672 3), some of them possibly associated with the effusion of obsidian lava flows. Proximal-  
673 medial multiple-metre thicknesses of pumice fall deposits from Bora and/or Baricha are also  
674 consistent with eruptions up to VEI 5. Limited accessibility prevents us from obtaining more  
675 detailed magnitude estimates for the scale of these important eruptions. The most  
676 prominent recent explosive eruption of the Boset-Bericha complex was that of the sub-  
677 Plinian “Boset Pumice”.

678 Conservative estimates of VEI 3-4 eruptions and corresponding minimum deposit  
679 volumes of 0.01 km<sup>3</sup> and 0.1 km<sup>3</sup> (Pyle 2015, 2016) allow us to semi-quantitatively constrain  
680 first-order eruptive rates in the Holocene for some MER volcanoes. Based on the rapid  
681 thinning trends of Qup (Fig 5; see above) we assign a magnitude of 3 to all of the 25 Aluto  
682 deposits in the last 12,000 years (Table 2) and a magnitude of 4 to 4 of the 7, and magnitude  
683 3 to the 3 remaining, Corbetti eruptions constrained on land (based on relative thicknesses  
684 in the proximal sections; Fig 3). This results in a minimum estimate of volumetric eruptive  
685 rates of 0.01 – 0.1 km<sup>3</sup> / ky at these two volcanoes (assuming 800 kg/m<sup>3</sup> of deposit density,

686 and 2380 kg/m<sup>3</sup> peralkaline rhyolite density, in the absence of other constraints from e.g.  
687 water content; Neave et al. 2012), substantially less than the 0.5 – 0.75 km<sup>3</sup> / ky constrained  
688 for the mid-Pleistocene “silicic flare-up” in the CMER (primarily Aluto and Corbetti), the  
689 period during which most of the calderas were formed (Hutchison et al. 2016c). These  
690 modern eruptive rates are also lower but broadly comparable with those estimated for the  
691 highly explosive trachytic Rungwe and Ngozi volcanoes in southern Tanzania (ca. 0.25 km<sup>3</sup> /  
692 ky; Fontijn et al. 2010, 2012). Note that the above estimates (except for the “flare-up” ones  
693 of Hutchison et al. 2016c) do not take into account the effusive eruptive products and are  
694 based on minimum eruptive volumes, therefore represent minimum rates.

695 At Aluto and Corbetti most of the obsidian lava flows and *coulées* are presumably  
696 associated with an explosive eruption either preceding or following the effusive phase  
697 (Hutchison et al. 2016b; Di Paola 1972). This is consistent with the ubiquitous presence of  
698 pumice deposits on both edifices, and is observed on other peralkaline volcanoes producing  
699 pumice cones and obsidian lavas (Dellino and La Volpe 1995; Mahood and Hildreth 1986).  
700 Further north along the MER, at Tullu Moye, but particularly Boset-Bericha and Fentale  
701 there is a generally increasing proportion of silicic effusive (obsidian lava flows) over  
702 explosive volcanism. At Tullu Moye several of the most recent silicic eruptions have been  
703 effusive and emplaced thick obsidian lava flows. We did not encounter evidence of an  
704 associated explosive eruption, though the historical accounts of the youngest eruption do  
705 suggest the occurrence of ash fall (Gouin 1979). The strongly fault-controlled Boset-Bericha  
706 complex has experienced both effusive and a limited number of explosive eruptions in its  
707 most recent phases, with most of the edifices built up by silicic lava flows (Fig 10; Sieburg  
708 et al. 2018). At Fentale, silicic post-caldera volcanism seems dominated by obsidian lava  
709 flows, possibly with a small component of associated explosive activity.

710

711       ***4b. Volcano-tectonic interactions and mafic volcanism along the MER***

712       Active faults of the Wonji Fault Belt cross-cutting Fentale, Kone and Gedemsa facilitate the  
713       eruption of basaltic magmas, forming scoria cones and lava flows. At Kone, post-caldera  
714       activity is entirely dominated by such small-scale basaltic lava flows and scoria-cone-building  
715       eruptions and no silicic products are identified in the post-caldera stage. Also at Gedemsa,  
716       the youthful nature of the faults cross-cutting the eastern sector of the caldera, and their  
717       aligned scoria cones (Fig 7), are indicative of a predominance of basaltic volcanism over  
718       silicic volcanism in the present stage. It has been suggested that the post-caldera basaltic  
719       products at these three volcanic complexes should not be considered as part of their  
720       respective predominantly silicic complexes, but represent a renewed phase of basaltic  
721       activity purely related to the Wonji Fault Belt (Giordano et al. 2014; Gibson 1974).

722       At Tullu Moye and Boset-Bericha, the Wonji Fault Belt however controls the eruption of  
723       both mafic and silicic magmas, which have clearly erupted contemporaneously in the recent  
724       past (Fig 7, 10-11; Siegburg et al. 2018). The southernmost clear surface expression of the  
725       Wonji Fault Belt is the field of basaltic scoria cones east of Lake Ziway (Fig 1). Whereas this  
726       basaltic volcanism is generally assumed to be cogenetic with the silicic products erupted  
727       from the post-caldera edifice of Aluto (Hutchison et al. 2016b), the detailed spatial and  
728       temporal relationships are not well constrained.

729       At Aluto and Corbetti all the basaltic (and presumably post-caldera) surface  
730       manifestations of volcanism occur well outside the known extent of the calderas and this  
731       may reflect the presence of a higher proportion of silicic melt in the crust relative to some of  
732       the other systems where basalt erupts along fractures cross-cutting the calderas (Kone,

Gedemsa). The larger amounts of silicic crustal melt would in this case prevent the denser basaltic melt to rise up through the caldera and instead deflect it to a “shadow zone” outside the caldera (e.g. Hutchison et al. 2016a; Mahood 1984; Mahood and Hildreth 1986; Jeffery et al. 2016).

#### ***4c. Implications for volcanic hazards***

Our tephrostratigraphic records for Aluto and Corbetti provide evidence for explosive eruptions at these volcanoes in the Holocene of up to 1-3 explosive events per millennium. Most of these eruptions have been of moderate scale but especially at Corbetti, some appear to be VEI 4-5. The largest Holocene explosive eruptions in the MER deposited several tens of centimetres of pumice and ash in areas which today are densely populated rural areas or urbanised population centres. The Boset Pumice eruption generated a pumice fall deposit of  $>0.5 \text{ km}^3$ , with a deposit thickness of ca. 20 cm in the city of Adama. The most recent large eruption at Corbetti (WKYP) shows a Plinian-style elliptical dispersal pattern, with a dispersal axis to the E and deposition of ca. 50 cm of pumice fall in the town of Shashemene and possibly more than 10 cm in the city of Hawassa (Fig 2). Such deposit thicknesses are sufficient to cause widespread damage and disruption to infrastructure and agriculture (e.g. Ayris and Delmelle 2012; Wilson et al. 2012). The dispersal axes as constrained from these deposits are not all consistent with the present-day dominant wind directions at this latitude (very minor to the SW or NE) but this may be due to the close proximity to the Intertropical Convergence Zone and its possible shifts throughout the Late Quaternary (e.g. Gasse 2000; Lézine et al. 2017).

The Bedded Pumice deposit of a large explosive eruption of Corbetti preceding WKYP has entirely overlapping major element composition (Fig 3), and shows rapid thinning away from the vent (i.e. more cone-like deposition, in contrast to sheet-like for WKYP; Fig 2). This is consistent with the rhythmically-bedded nature of its proximal deposits, which have built up a pumice cone (Fig S1b). Such crude parallel bedding, typically represented as gradual alternations of fine and coarser pumice lapilli at a dm-scale, reflects temporal variations in eruptive intensity and is commonly found in the pyroclastic fall deposits of most MER volcanoes and other peralkaline rhyolite volcanoes such as Pantelleria (Orsi et al. 1991) or Monte Pilato (Lipari; Davì et al. 2011) in Italy. These variations may reflect a typical pulsating style of activity controlled by the degassing dynamics in these moderately low-viscosity, crystal-poor magmas (Di Carlo et al. 2010; Di Genova et al. 2013; Neave et al. 2012); however the eruption dynamics, including initiation, evolution and duration of events, and resulting tephra dispersal patterns of pumice cone forming eruptions remain poorly understood.

#### ***4d. Chronology and preservation***

In the latest Pleistocene and Holocene timeframe, the scarcity of useful material for radiocarbon dating (e.g. charcoal embedded in pyroclastic deposits) from terrestrial sections in the MER provides a great challenge to constrain absolute chronologies and eruptive rates of silicic vs. mafic volcanism. In the absence of absolute chronologies, subtle variations in glass major element chemical composition between otherwise similar deposits allow us to fingerprint units and constrain relative stratigraphies and minimum amounts of eruptive events in the recent geological past. At some volcanoes however, additional chemical data

778 such as glass trace element or mineral major element composition (e.g. Albert et al. 2012;  
779 Rawson et al. 2015) might allow us to refine correlations in addition to stratigraphic  
780 constraints.

781 The most detailed records of Late Quaternary eruptions are from settings where  
782 pyroclastic deposits are interbedded with lacustrine deposits containing macrofossil remains  
783 (Corbetti, Aluto). At Aluto, the Late Quaternary pyroclastic – lacustrine sequences exposed  
784 on land as a result of extensive lake level fluctuations (Benvenuti et al. 2002, 2013; Le Turdu  
785 et al. 1999) provide scope to integrate these sequences with lake sediment cores (Chalié  
786 and Gasse 2002) into a robust chronological framework that allows the study of temporal  
787 variations in and interactions between volcanism, tectonic activity and the  
788 palaeoenvironment.

789 Deposition of pyroclastic deposits in lakes may favour their preservation in the geological  
790 record, as the terrestrial environment is more prone to weathering and erosion; and it is  
791 well known that lacustrine sequences tend to preserve more complete records of volcanism  
792 than terrestrial sequences alone (e.g. Bertrand et al. 2014; Fontijn et al. 2016; Green et al.  
793 2016). The lack of exposed lacustrine sequences North of Aluto does therefore potentially  
794 bias the preserved record to the largest of events. Note, however, that apart from near  
795 Aluto, most of our studied sections at all the other volcanoes are in fact terrestrial. It is  
796 possible that the relatively small-scale (e.g. VEI 3 and below) events are missing from these  
797 sequences, but we would expect abundant evidence for VEI 4 and above events to be  
798 preserved in soil sequences had they occurred in the recent geological past (e.g. Brown et  
799 al. 2014; Fontijn et al. 2010; Pyle 2016).



The new geochemical data and observations of proximal pyroclastic deposits from all the major silicic MER volcanic complexes presented in this paper will allow improved tephrochronological correlations between Late Quaternary sedimentary archives across central Ethiopia (e.g. Martin-Jones et al. 2017; Tiercelin et al. 2008). Such regional-scale correlations of proximal with more distal records will in return allow the fine-tuning of our eruptive chronologies and frequencies, as well as constrain eruption magnitudes and dispersal patterns important for future hazard assessment. Studies limited to tephras in lacustrine settings (e.g. Martin-Jones et al. 2017) may provide constraints on frequencies of events, but cannot highlight the complexity and diversity of eruptive styles and eruption dynamics. At best such studies are complementary to field-based volcanology to understand volcanic hazards. It is critical that this complexity is well-documented, including from detailed field observations of proximal deposits, before undertaking hazard assessments that ultimately feed into risk management policies.

## **5. Conclusions**

Geological evidence and current geophysical unrest at many (Biggs et al. 2011; Hutchison et al. 2016a) on-axis silicic MER volcanoes suggests that they remain active and are likely to erupt again in the future. Here we present new fieldwork and geochemical data of late Quaternary silicic tephra deposits in the MER. Our work suggests that potential volcanic hazards and risks at the central MER silicic caldera systems vary widely between each complex, despite similarities in their structure, chemical composition and long-term evolution. Corbetti and Aluto have both been highly active in the Late Quaternary. Their eruption frequencies of 1-3 events per millennium place them amongst the most frequently

active volcanoes for moderate-scale explosive eruptions in East Africa. Some recent MER eruptions were of sub-Plinian scale, depositing tens of centimetres of pumice and ash at present-day densely populated rural areas as well as urbanised population centres. In addition to evidence of explosive activity, most silicic MER complexes have also experienced recent silicic effusive activity in the form of thick obsidian lava flows. The striking variety of eruptive style and rates at the seemingly similar volcanoes along the MER requires a detailed evaluation of volcanic hazard and risk at a regional scale in this (and other) part(s) of the East African Rift System to incorporate reconnaissance studies on each individual centre, and questions the use of analogies to inform hazard and risk mitigation policies.

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## Figures

**Fig 1** Overview of Main Ethiopian Rift with Late Pleistocene – Holocene active volcanic centres, small eruptive centres and main tectonic features. Outcrops visited (yellow dots) span most of the MER; lake sediment cores with described tephra horizons indicated in blue. For clarity, the Wonji Faults are not drawn; they largely control the spatial distribution of basaltic small eruptive centres along the rift axis.

**Fig 2** Isopach map of Wendo Koshe Younger Pumice (WKYP, turquoise) deposit from Corbetti as identified from lateral tracing in the field and geochemical analysis. Thicknesses of individual measurements in cm; contours are drawn tentatively where dispersal is poorly constrained. Thickness values for Bedded Pumice (in orange) are also given in cm but no contours are drawn. Reference sites for stratigraphy (named MER- and 3-digit number) are schematically illustrated in Fig 3. Caldera wall and post-caldera edifices are also outlined (A: Artu, U: Urji, C: Chabbi). Extra-caldera small eruptive centres (SECs) to the east of Lake Hawassa are basaltic and possibly phreatomagmatic in origin (Rapprich et al. 2013). A rhyolitic tuff complex immediately north of the lake is overlapped by Chabbi obsidian flows and may also be phreatomagmatic. Other SECs, in the form of magmatic scoria cones, occur north of Corbetti along fractures extending to the Shala Caldera. Post-caldera Tullu Fike

pumice cone complex indicated north of Shala. Other extra-caldera vents north and south of the caldera, and presumably of basaltic composition, are also of unknown age.

**Fig 3** Schematic representation of Corbetti's composite Holocene pyroclastic stratigraphy; locations of reference sites indicated on Fig 2. Inset shows major element analyses of distinct pyroclastic units revealing systematic pantelleritic composition. Non-correlated Corbetti units indicated as small grey dots. Names and ages of Lake Tilo (TT-) and Hawassa (AWT-) tephras after Martin-Jones et al. (2017).

**Fig 4** Field photographs for reference sections of Holocene pyroclastic deposits shown in Fig 2-3 (Corbetti) and Fig 5 (Aluto); same colour coding. **(a)** Coarse pumice lapilli breccia of WKYP covering finer grained Bedded Pumice; black arrow denotes ca. 10-15 cm palaeosol between deposits. **(b)** Oldest sequence of Holocene pyroclastic deposits exposed in terrestrial sections as described in this study; black arrow shows sample location of charcoal dated  $7.75 \pm 0.04$  ka cal BP (Table 3); people for scale; **(c)** Exposure of lacustrine deposits interbedded with pyroclastic deposits (typically darker grey horizons) in type section A01 (Fig 5); **(d)** Close-up of pyroclastic deposit inferred to be emplaced under water: bottom half clast-supported pumice lapilli with some intergranular fine ash, top half pumice lapilli dispersed in more ash-rich matrix; pencil for scale

**Fig 5** Spatial distribution of sample localities at Aluto, with identification of type locality A01 (stratigraphic column on right); some locally correlated deposits colour-coded as in Fig 6, with deposit thickness indicated in cm; tephra from other sites (grey dots) did not yield correlations across multiple localities. Selected named outcrops also represented in Fig 4c-d, 6 and S1c-d ("MER" omitted from the 3-digit labels for clarity, "WH\_" omitted from other

labels; full details in Supplementary Table 2). SEC: Small Eruptive Centre – those close and possibly associated to the Aluto complex are distinguished from the ones in East Ziway; TC: tuff cone; TAC: trachyandesitic scoria cone. High-resolution LIDAR digital elevation model on the Aluto edifice after Hutchison et al. (2015).

**Fig 6** The glass major element composition of geologically young Aluto pumice samples. These span a wide range of mostly pantelleritic compositions. Some units can be correlated on a local scale, including A9 / Qup. Samples highlighted in colour are are colour-coded as in Fig 5; grey dots represent analyses of samples that could not be correlated between multiple localities. Glass chemistry for Corbetti samples (Fig 3) given for comparison, and to highlight potential correlation of sample 150207 found NE of Lake Langano (Fig 5) to Corbetti source (Fig 3). The complicated fingerprinting of Corbetti samples however requires additional verification to validate this correlation.

**Fig 7** Overview map of Bora-Baricha, Tullu Moye and Gedemsa area. Both post-caldera scoria cones near Gedemsa and Tully Moye, as well as rhyolitic lava flows of Tullu Moye are controlled by the Wonji Fault Belt. SECs indicated in orange have confirmed basaltic glass composition (samples MER153A and MER157A in Supplementary Table 3a). Gedemsa caldera is outlined in dark blue, with extent of its post-caldera constructs in pink. The dotted pink lines highlight low-relief dome-shaped constructs which are presumably also post-caldera centres of activity. Dots indicate sample sites, and those at Gedemsa are colour-coded as in Figure 9. Selected outcrops from Figures 8-9 (omitting “MER-“, for clarity; Supplementary Table 2) are named.

**Fig 8 (a)** Bora-Baricha representative field photos showing alternation of pyroclastic fall deposits and palaeosols (MER147-1/2) and a stack of multiple-metre-thick pyroclastic fall and dilute PDC deposits alternating with poorly developed soils and ash-rich reworked horizons (MER150). These deposits have not been chemically correlated to other units in the region but were most likely sourced from Bora-Baricha or associated edifices; colour-coded with (b) and (c). **(b)** Bora-Baricha and Tullu Moya key stratigraphic sections, spanning all sides of the complex (Fig 7). Many eruptions have emplaced several meters of pyroclastic fall deposits, and most sections show only limited soil formation between events. **(c)** Glass major element composition of Bora-Baricha and Tullu Moya silicic pyroclastic deposits. Bora-Baricha samples are pantelleritic whereas those of Tullu Moya are comenditic. The top unit of section MER150 has a distinct composition to the rest of the sequence and may form a fractionation trend with Tullu Moya comendites.

**Fig 9 (a-c)** Gedemsa representative field photos: **(a)** MER084, crudely bedded dark grey pumice lapilli breccia alternating with low-angle cross-bedded fine pumice and ash lapilli deposits, presumably related to caldera-forming events, and chemically correlated to MER077; scraper (encircled in yellow) for scale. **(b)** MER087: poorly sorted pumice lapilli and bomb breccia exposed on rim of Kore crater, the most prominent post-caldera centre; pencil for scale. **(c)** MER081: (presumably) post-caldera pumice lapilli breccia deposit exposed underneath cross-bedded indurated tuff deposits associated to mafic volcanism near the NE rim of the caldera. **(d-e)** Gedemsa glass geochemistry for a selection of samples obtained

from multiple syn-caldera pumice breccia deposits and post-caldera pumice deposits (colour-coded as in Fig 7). The three most FeO-rich deposits originate from the intra-caldera coalesced domes Kelo, Dima and Kore. Three more chemically distinct pumice fall deposits are identified and were sampled from sections immediately NE and E of the caldera. Each of these presumably represents an individual moderately explosive post-caldera eruption. The age of these post-caldera events is not known.

**Fig 10** Overview map of Boset volcanic complex, with overlain isopach map (thickness in cm) of the Boset Pumice deposit. Tephra was mainly dispersed westward, with accumulations multiple metres thick on the lower western flanks of the complex. The dispersal towards the north and east is poorly constrained; however none of the outcrops in those regions revealed the presence of substantial pumice fall deposits. Named outcrops are those listed in Fig 11. <sup>(1)</sup> One lobe of trachyandesitic lava was dated at  $4.2 \pm 3.2$  ka (Siegburg et al. 2018) and may correspond to Scoria #2 in our type section MER108 (Fig 11).

**Fig 11** Glass geochemistry and type stratigraphy of the most recent pyroclastic deposits at Boset volcanic complex; **(a)** Total Alkali – Silica diagram (after Le Bas et al. 1986) showing rhyolitic pumice deposits and basaltic scoria deposits. A scoria fall deposit interbedded in the type stratigraphy (unit #2) has a basaltic trachyandesite composition and possibly corresponds to the eruption of lava flows in the saddle between Gudda and Bericha (Siegburg et al. 2018). The most evolved rhyolites are from a sequence of altered coarse grey pumice fall deposits and finely parallel to cross-bedded dilute PDC deposits, which may relate to a caldera-forming event; **(b)** Classification diagram of peralkaline rhyolites (after MacDonald 1974) shows the three most recent pumice fall units to have a pantelleritic

composition, whereas the oldest pumice fall (#5) is comenditic. There may be multiple comendite falls but more field and geochemical data are required to verify this. Mafic samples in this plot are given for reference only. **(c)** Schematic log of type stratigraphic section for recent pyroclastic deposits, colour-coded as in **(a)** and **(b)**; **(d)** Field photograph of “Boset Pumice”, unit #1, in locality MER113 (Fig 10).

**Fig 12** Overview map of Kone caldera complex and Fentale, with indication of basaltic scoria cones which erupted as recently as 1810-1820 AD (Harris 1844; Supplementary Table 1). Fentale has experienced post-caldera silicic volcanism in the form of obsidian lava flows erupted from vents in the caldera floor and on the NE, E, SE and W flanks. At Kone there is no evidence for post-caldera silicic volcanism.

**Fig 13** Glass chemical composition of a selection of scoria fall deposits and pumice lapilli breccia associated to caldera-forming events at the Kone caldera complex. Corresponding map units of Rampey et al. (2010) indicated in brackets. Glass composition of obsidian source rocks from Kone after Negash et al. (2007).

## Tables

**Table 1** Average glass major element composition of main units at each volcanic centre (full dataset in Supplementary Table 3a)

**Table 2** Synoptic summary of MER post-caldera silicic and mafic eruptive activity, as constrained by edifice morphology, field observations, geochemistry, geochronology and previously published literature. Items for which no information is available have been left blank. PDC: pyroclastic density current.

**Table 3** New Accelerator Mass Spectroscopy radiocarbon date for charcoal sample buried under Corbetti pyroclastic fall deposit. Analysis was performed at Beta Analytic Inc., Florida, USA. Ages are reported as years before present (yr BP), “present” being 1950 CE, as per international convention. Calibration was performed in Oxcal v4.3 using the IntCal13 calibration curve (<http://c14.arch.ox.ac.uk>; Bronk Ramsey 2009; Reimer et al. 2013).

#### **Supplementary Information**

**Supplementary Figure S1** Field photographs for reference sections of Corbetti and Aluto Holocene pyroclastic deposits. **(a)** Stack of pyroclastic deposits separated by thin soil horizons representative of intra-caldera Corbetti sequence (including Bedded Pumice); black arrow denotes fall deposit within sequence of small-scale PDC deposits (Fig 3); people for scale; **(b)** Typically rhythmically bedded nature of Bedded Pumice in its proximal sections; trowel for scale; **(c)** Crudely bedded pumice fall deposits found ubiquitously on the edifice – type locality for “Qup” unit defined by Hutchison et al (2016b); scraper for scale. **(d)** Section through pumice cone displaying >10 m rhythmically bedded pumice and ash fall deposits; close-up observations of this sections were not possible due to steep cliff;

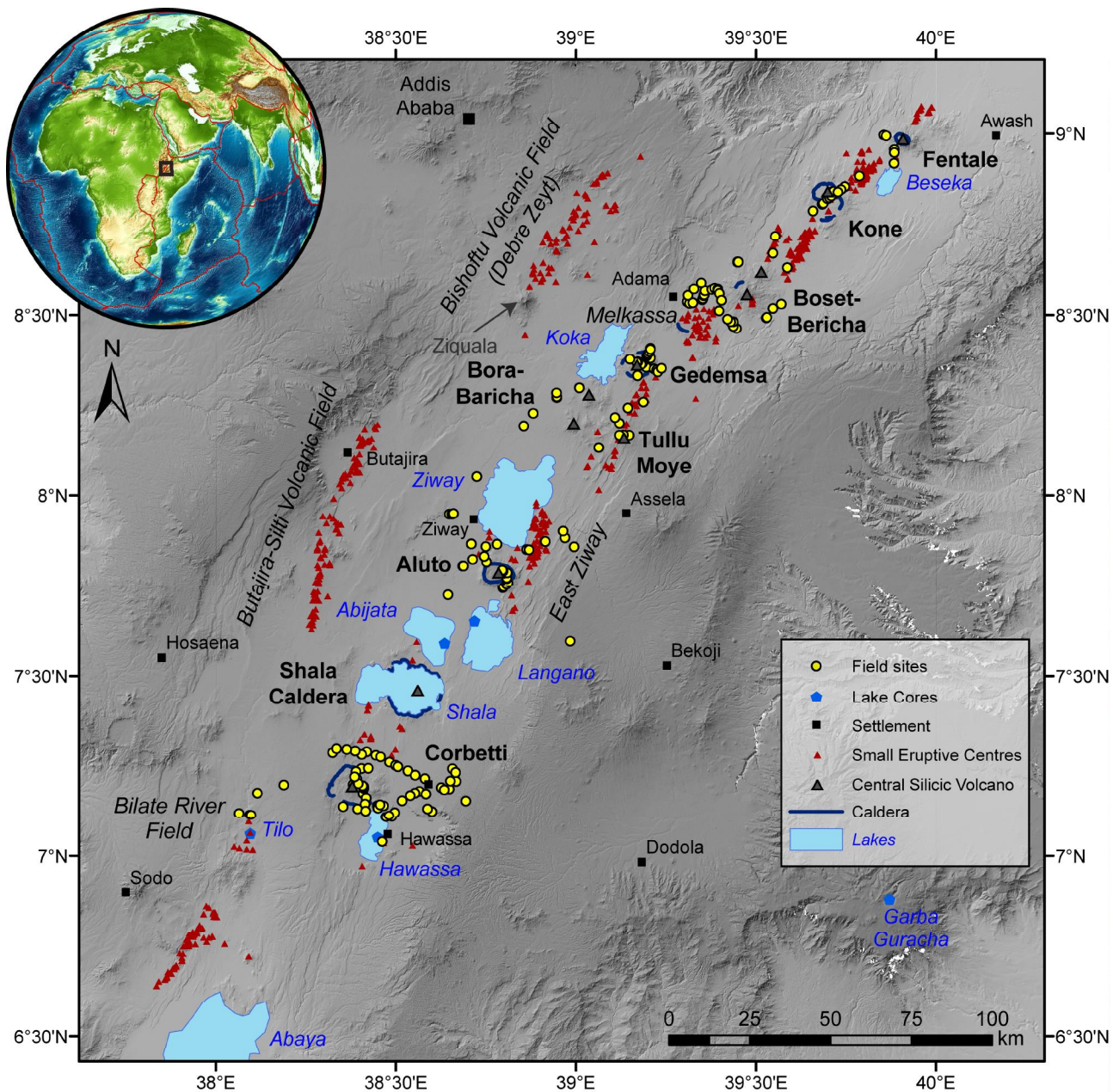
**Supplementary Table 1** Overview of central silicic volcanoes in the Main Ethiopian Rift (MER), with indication of their alternative names present in the literature and most recent confirmed eruption. Volcano Number after the Smithsonian Institute Global Volcanism Program Database (<http://volcano.si.edu>).

**Supplementary Table 2** Main Ethiopian Rift outcrop localities with brief description of geology. All coordinates in Latitude - Longitude, WGS84 datum. Sample names (as listed in Supplementary Table 3a) follow outcrop name followed by a letter (e.g. A, B, etc.).

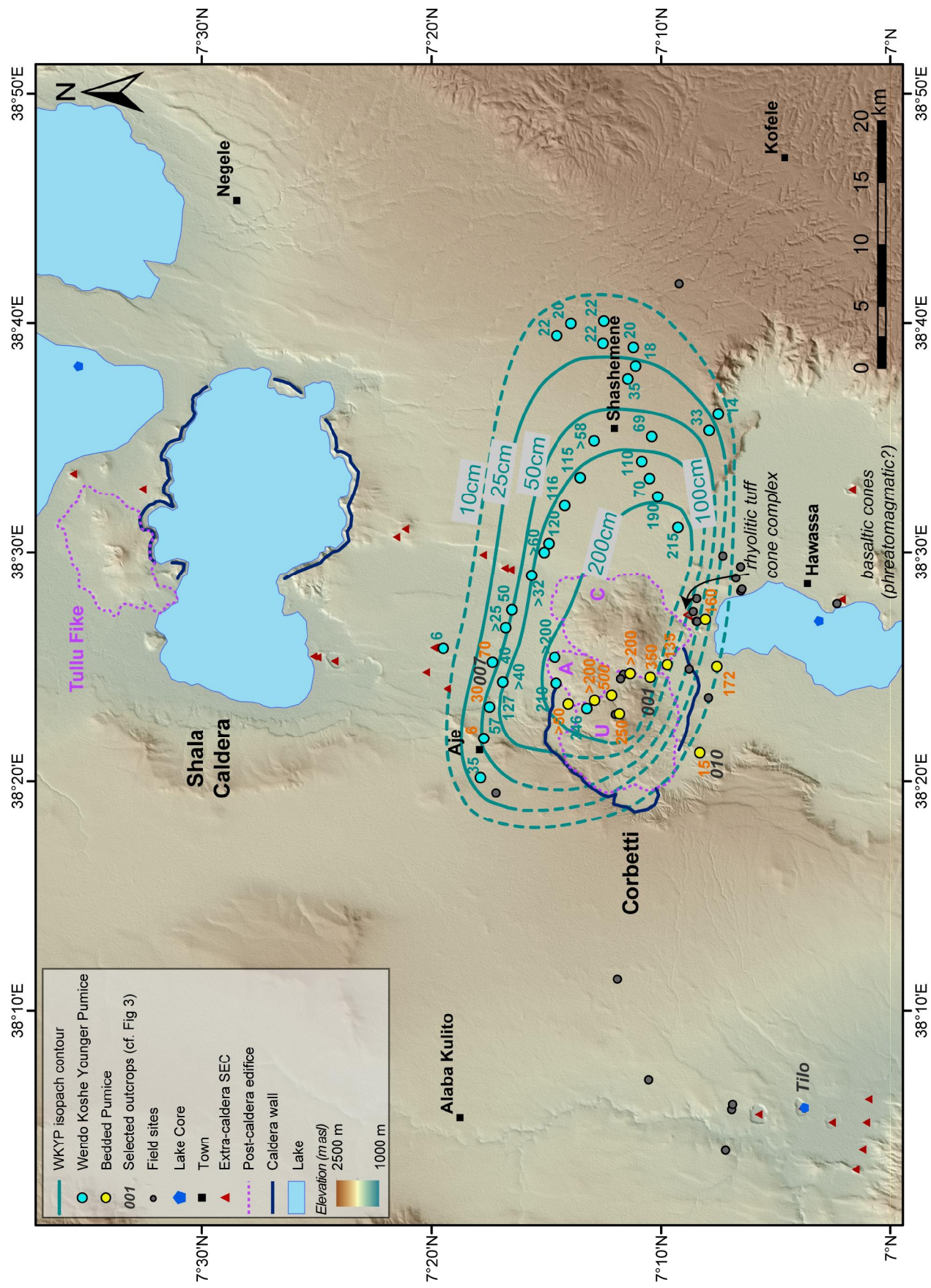
1411 **Table S3a.** EMP data for all samples analysed in this study. Outcrop coordinates for  
1412 terrestrial outcrops (names starting with "MER") are listed in Supplementary Table S2.  
1413 Points refer to individual analysis spots, each on an individual patch of glass, avoiding visible  
1414 crystals. Analyses suggesting an influence of (hidden) crystals have been omitted. Samples  
1415 are grouped by volcano (south to north, Fig 1) and units are identified where possible. Only  
1416 the most widely distributed units are given a unique name. Other units are identified as  
1417 "NA" followed by the unit number of their corresponding section (in stratigraphic order, #1  
1418 being the youngest). Run refers to date analyses were acquired; corresponding secondary  
1419 standard analyses and analytical conditions for all runs, ordered by date, are listed in  
1420 Supplementary Table S3b. Analyses are normalised to volatile-free composition. Cl was also  
1421 omitted from normalisation because it was not analysed for all samples.

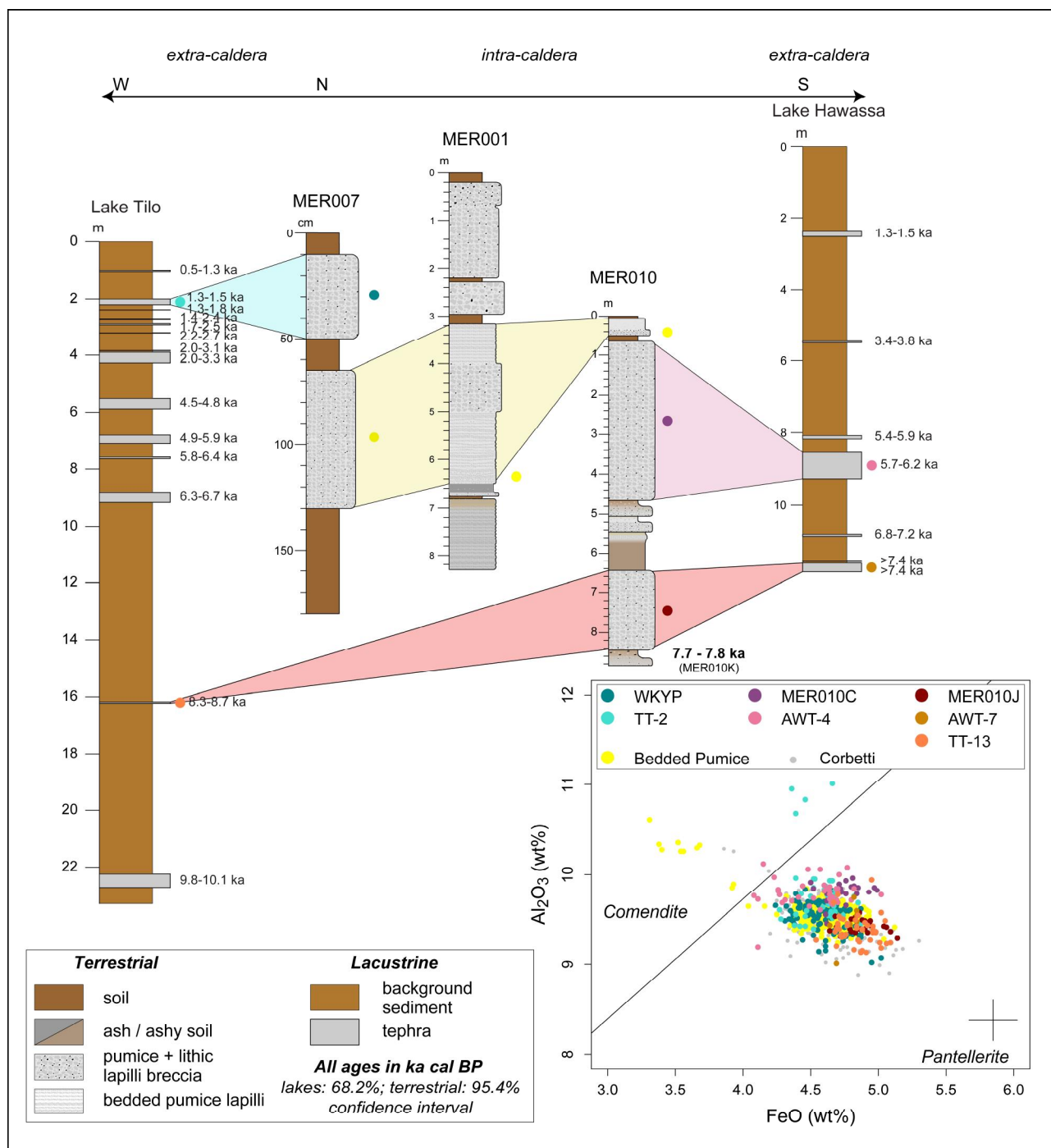
1422 **Table S3b** EMP analyses of secondary glass standards (non-normalised) run together with  
1423 samples. All analyses were run at 15 kV accelerating voltage, 6 (or 4) nA beam current, and  
1424 10 (or 5)  $\mu\text{m}$  beam width. Standards were run at the start, regularly during and at the end of  
1425 each run to monitor data quality. Error bars, also reported with the samples, are calculated  
1426 as 2 x relative standard deviation on the standard analyses and hence represent precision of  
1427 the data. Data accuracy is colour-coded on the average for each standard analysis during  
1428 each run: green values are within 1s of the preferred values, orange within 2s, and red out  
1429 of the 2s range. Standards used are ATHO-G (rhyolite), NIST-612 (synthetic glass), StHs6/80-  
1430 G (andesite/dacite) and ML3B-G (basalt), and cover the range of expected values in our  
1431 sample set. Preferred values, after Jochum et al. (2006, 2011), can also be consulted on  
1432 GeoREM (<http://georem.mpch-mainz.gwdg.de/>).





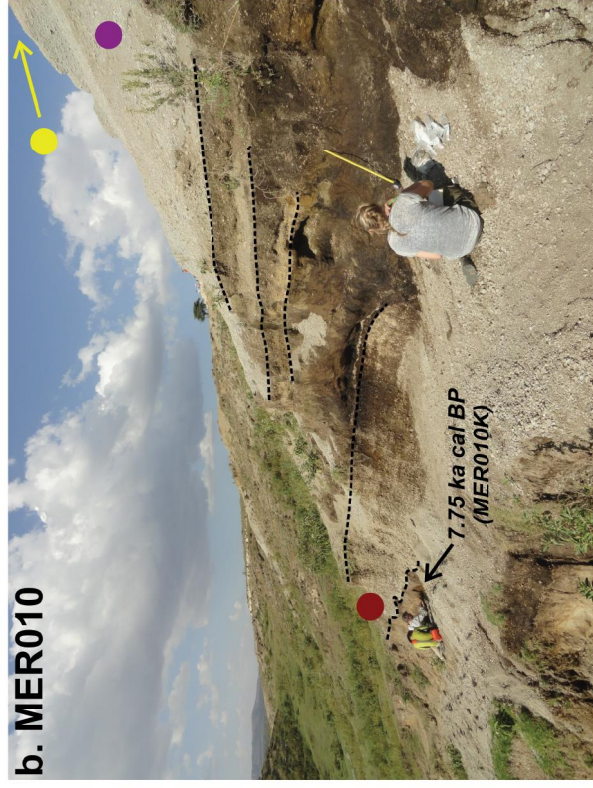
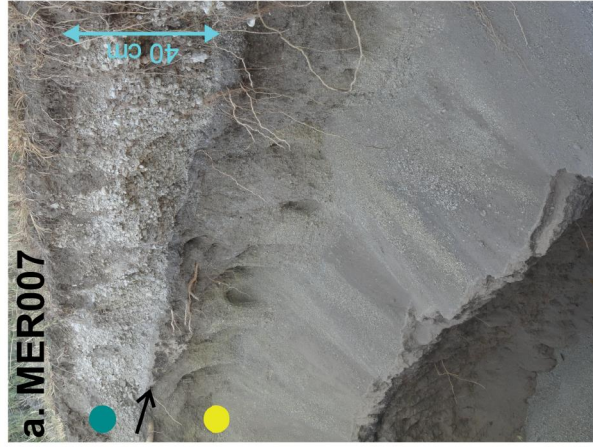




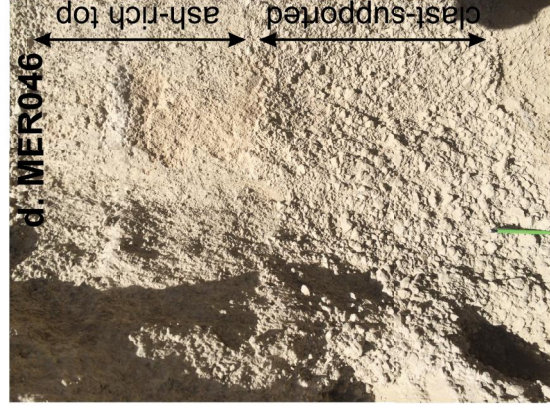




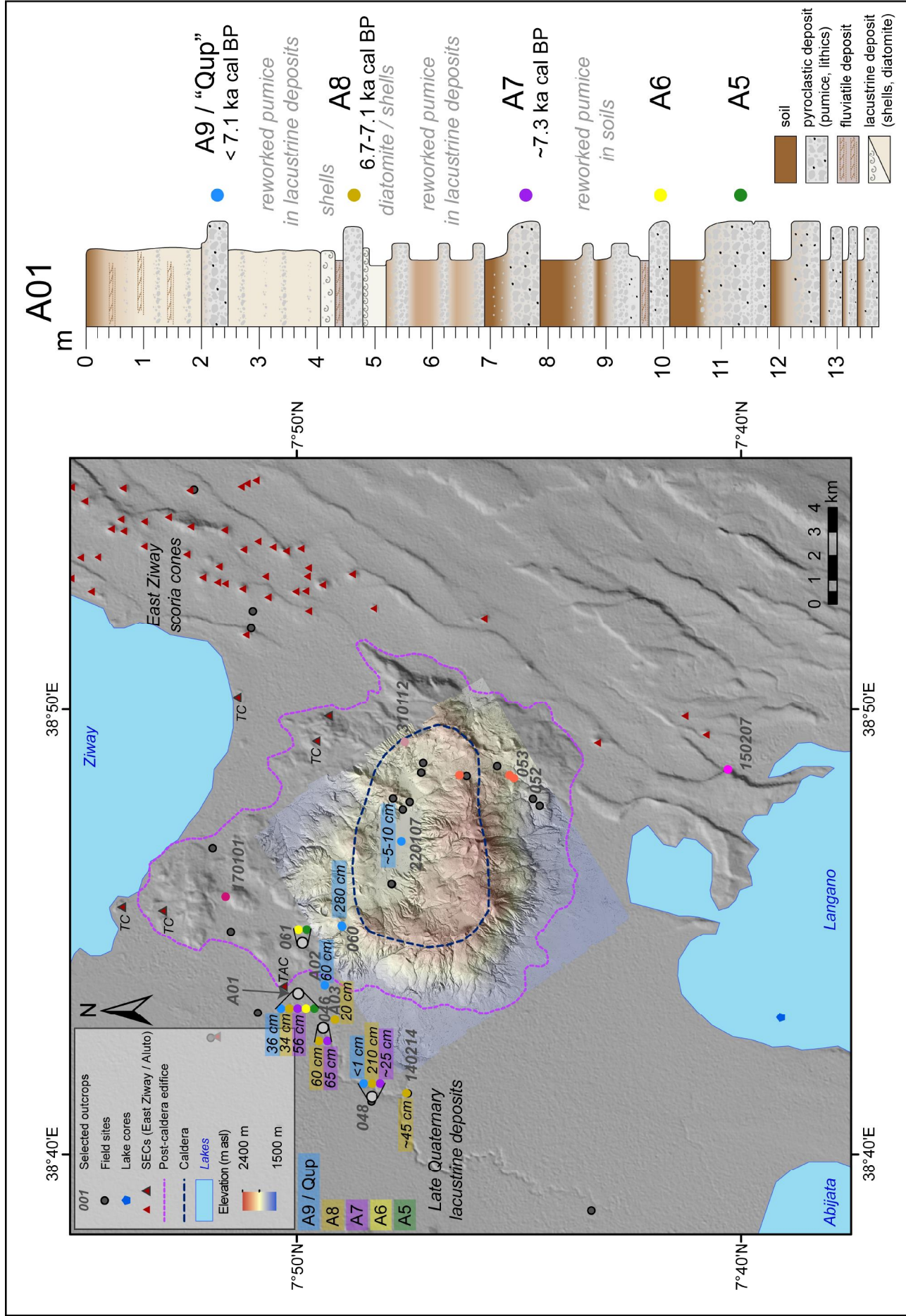
## Corbetti

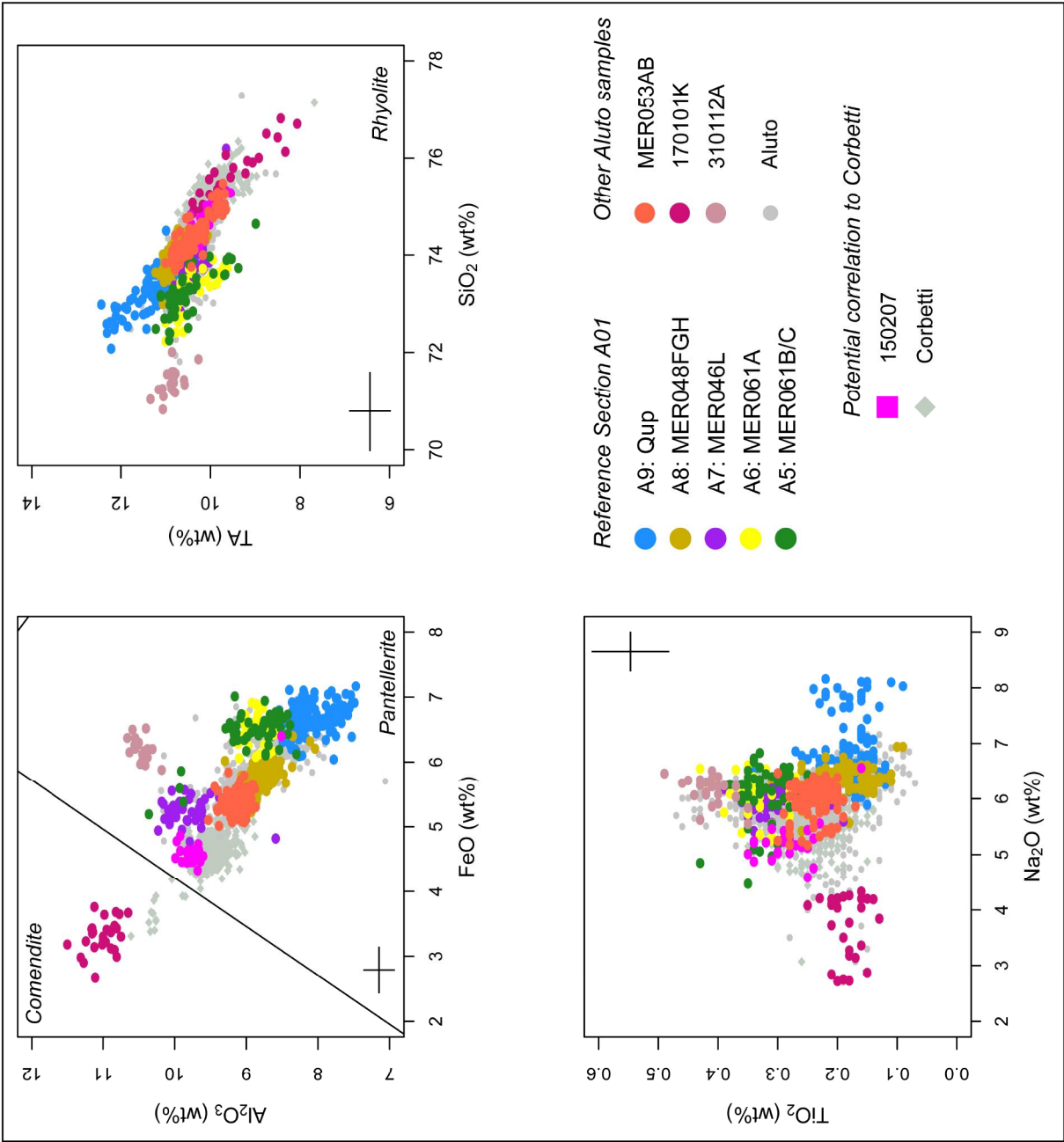


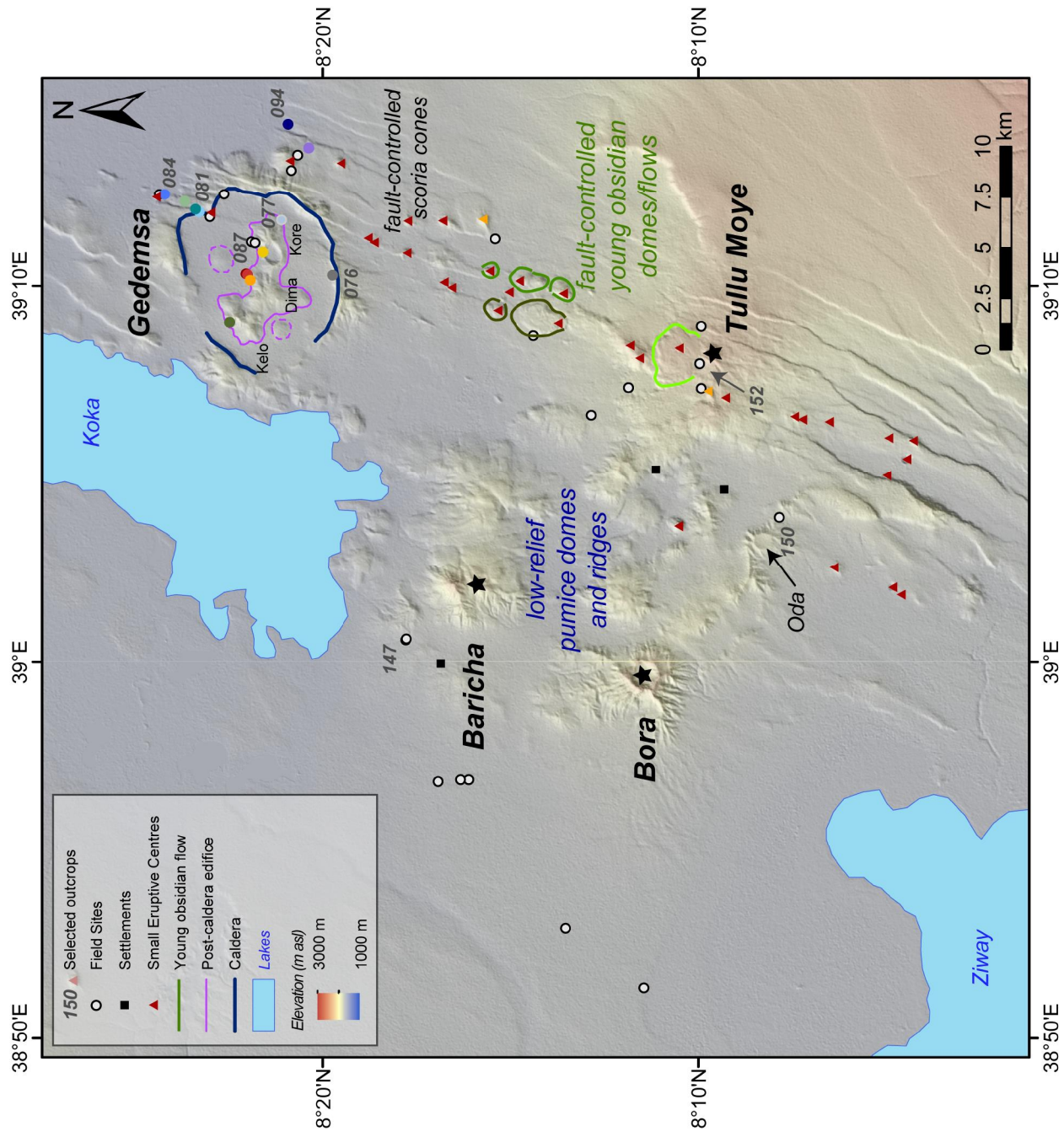
## Aluto



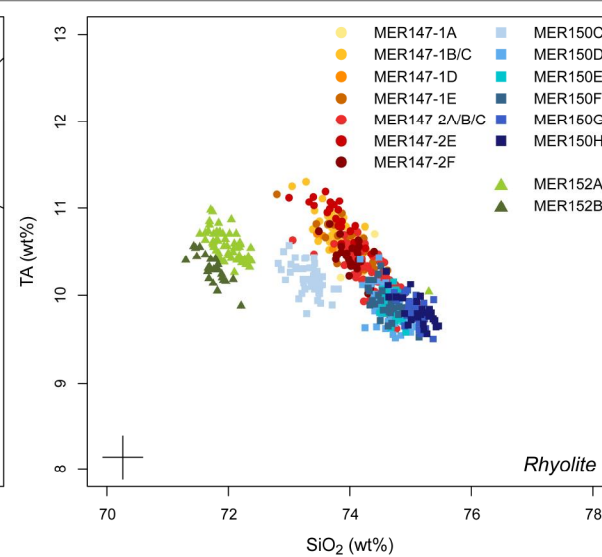
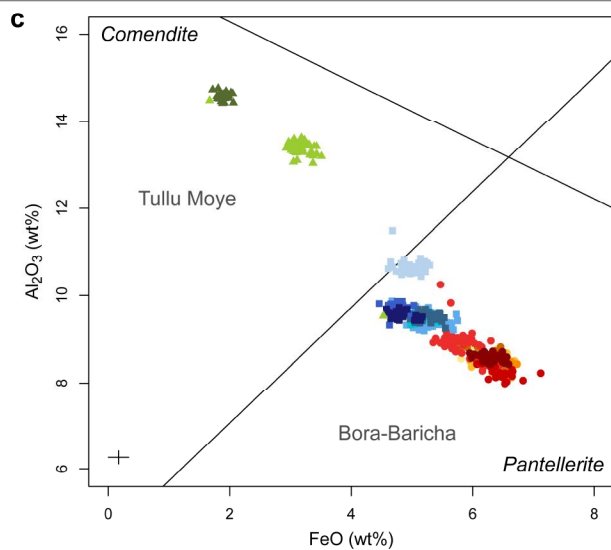
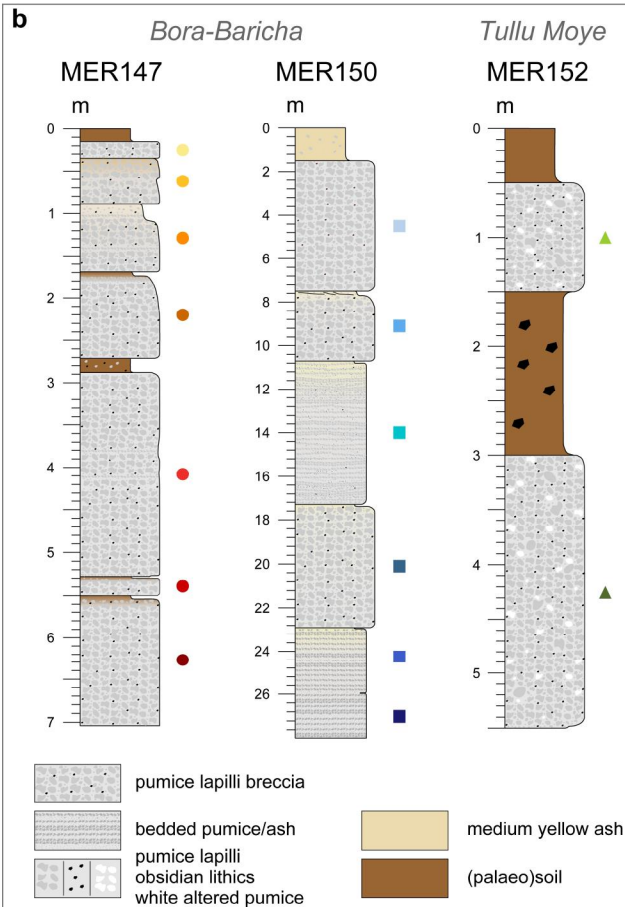




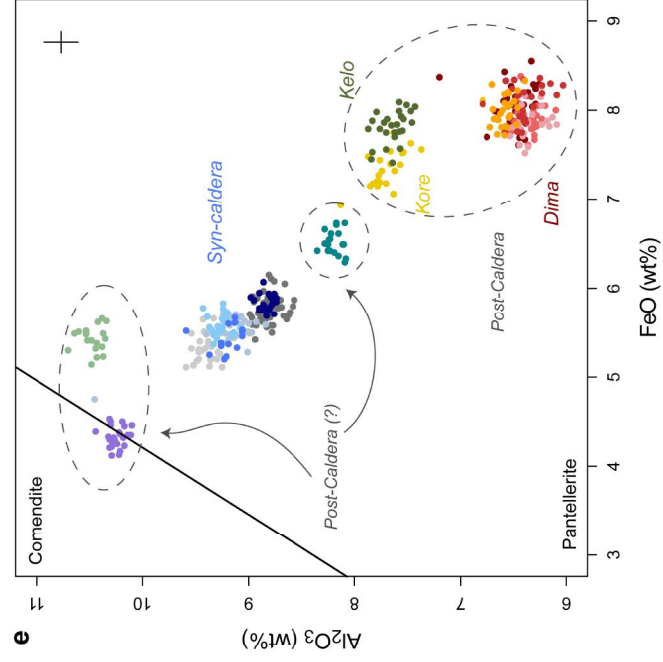
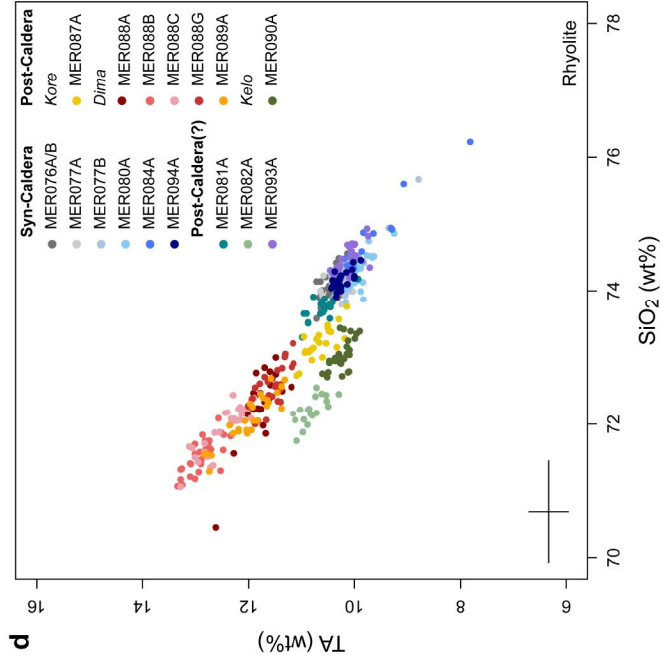
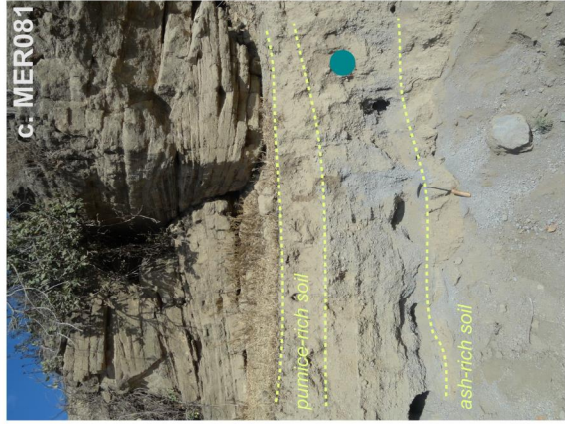
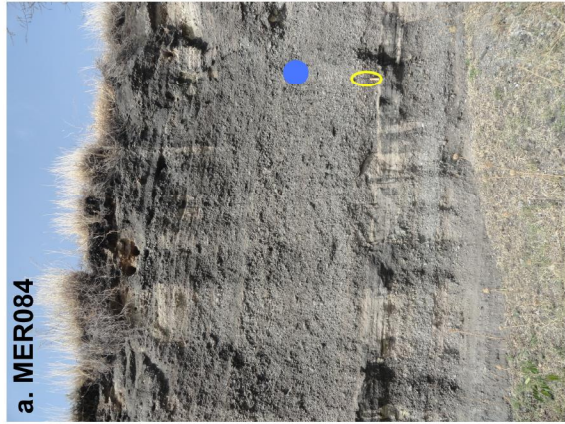


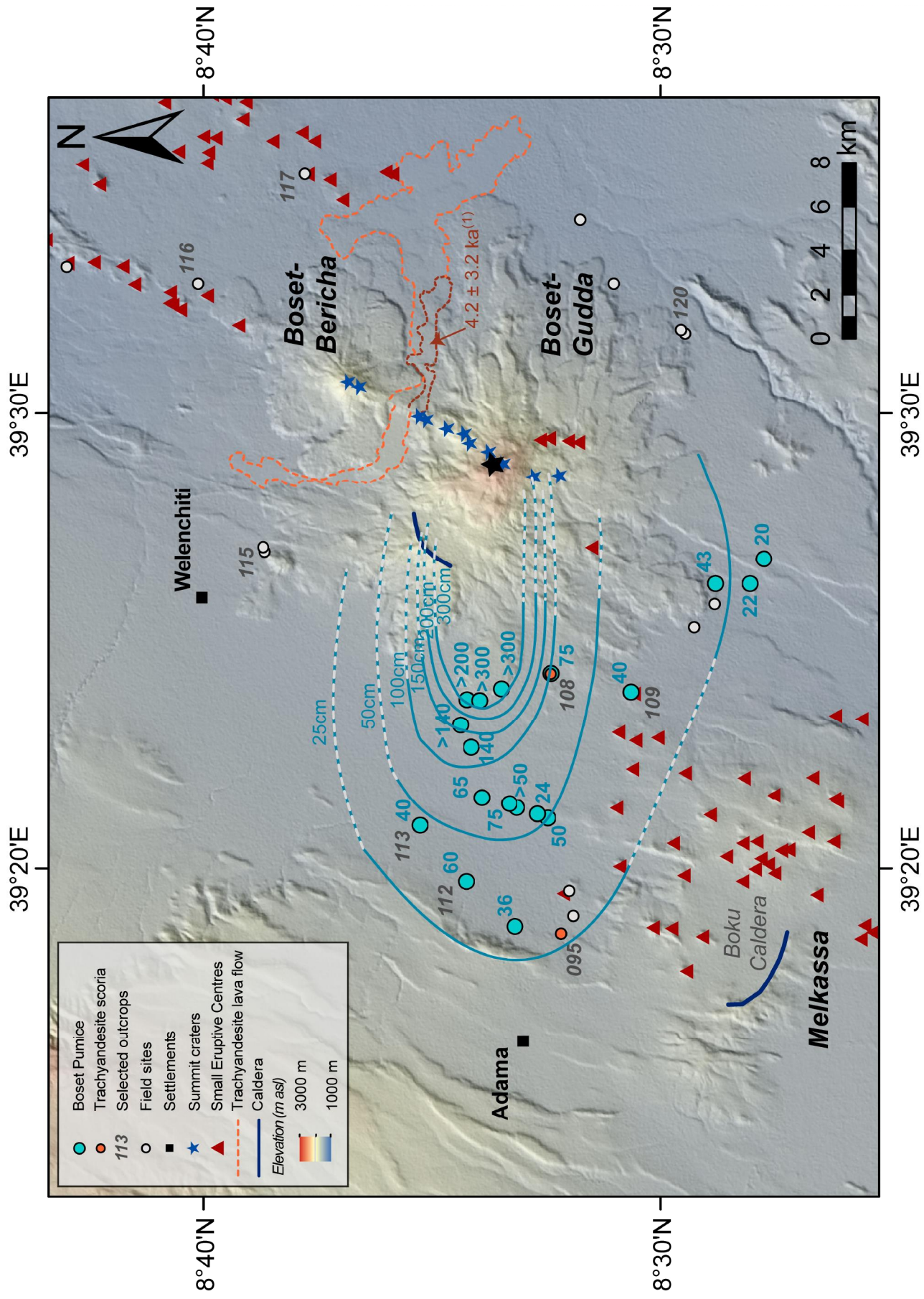




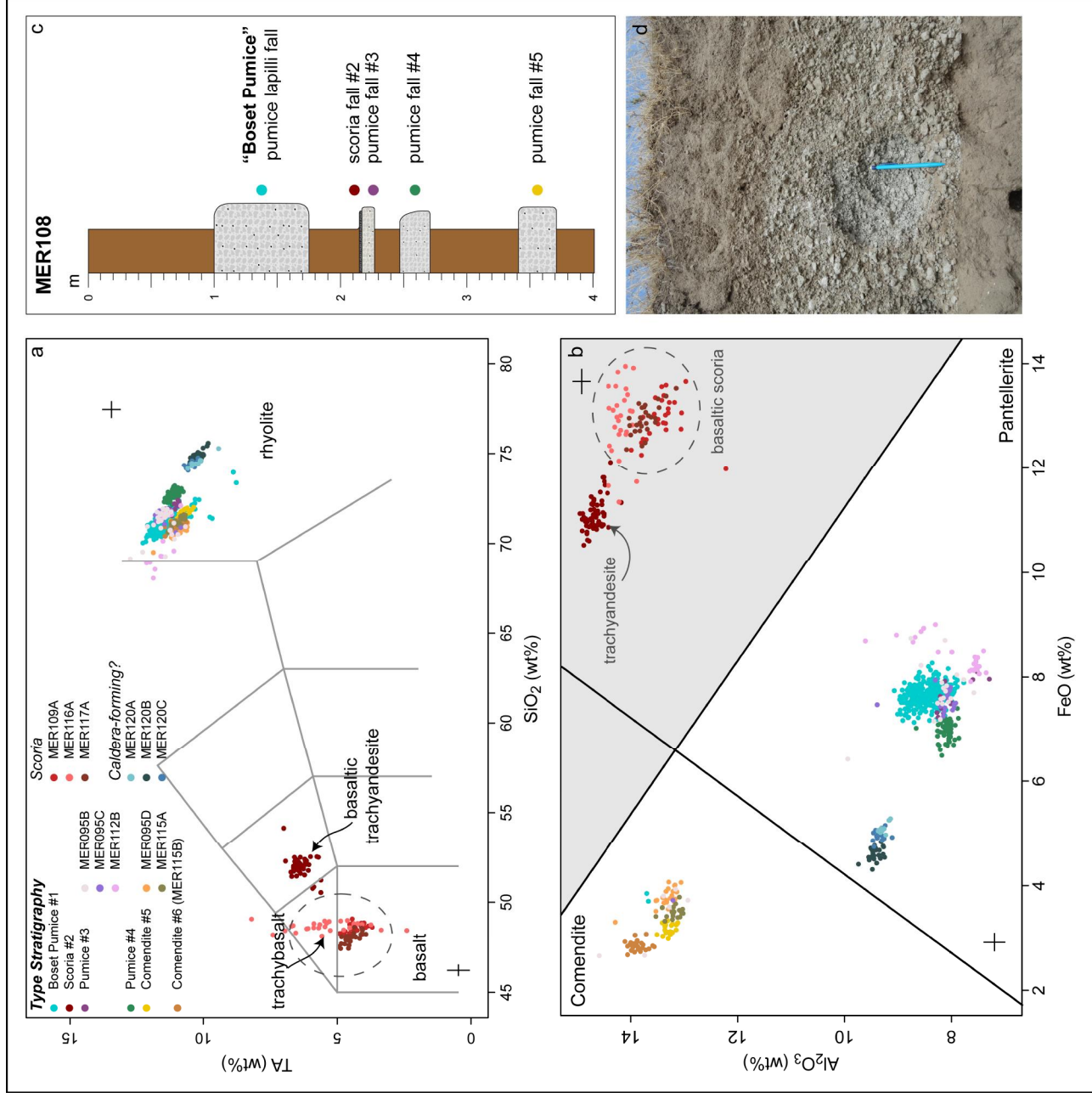


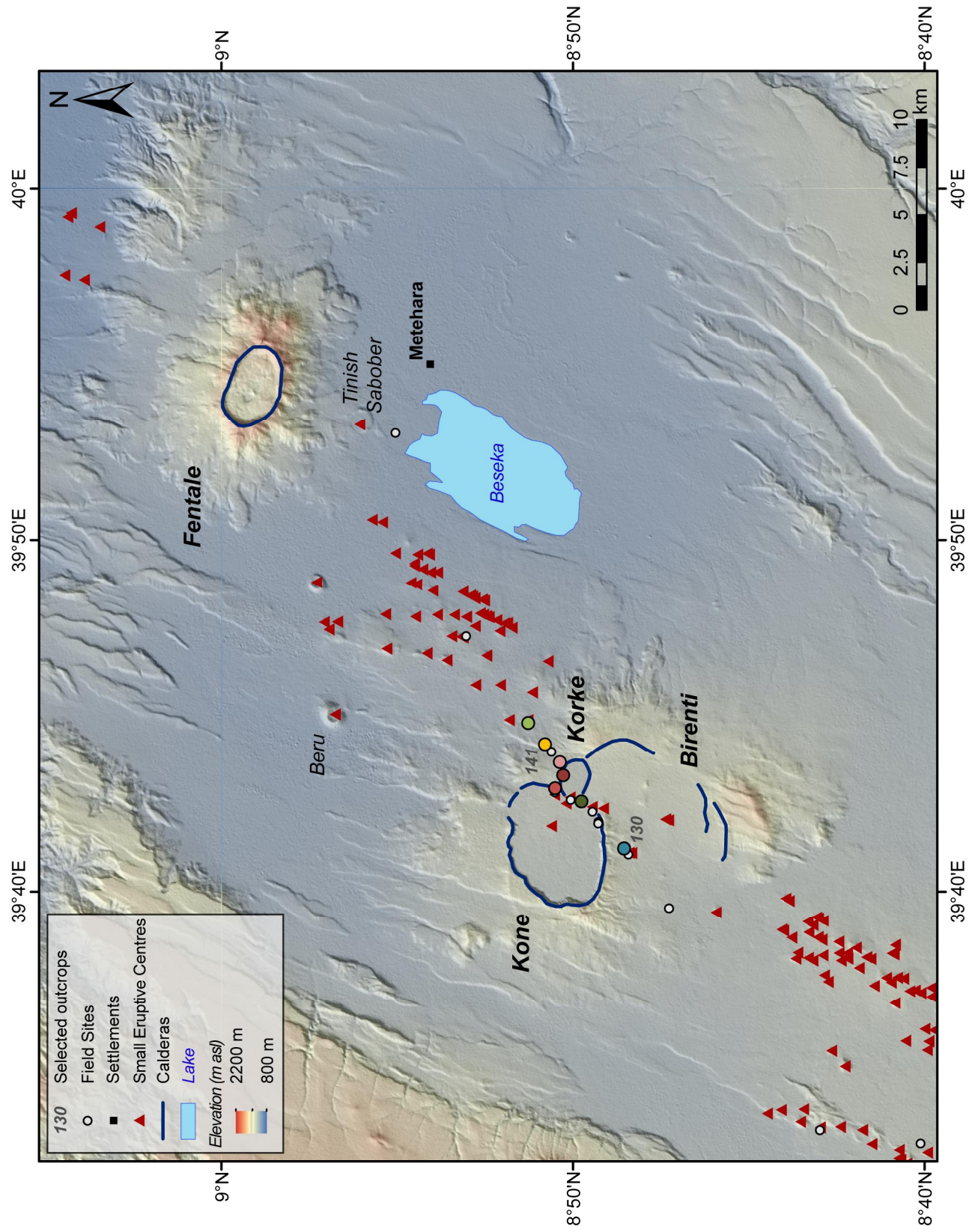


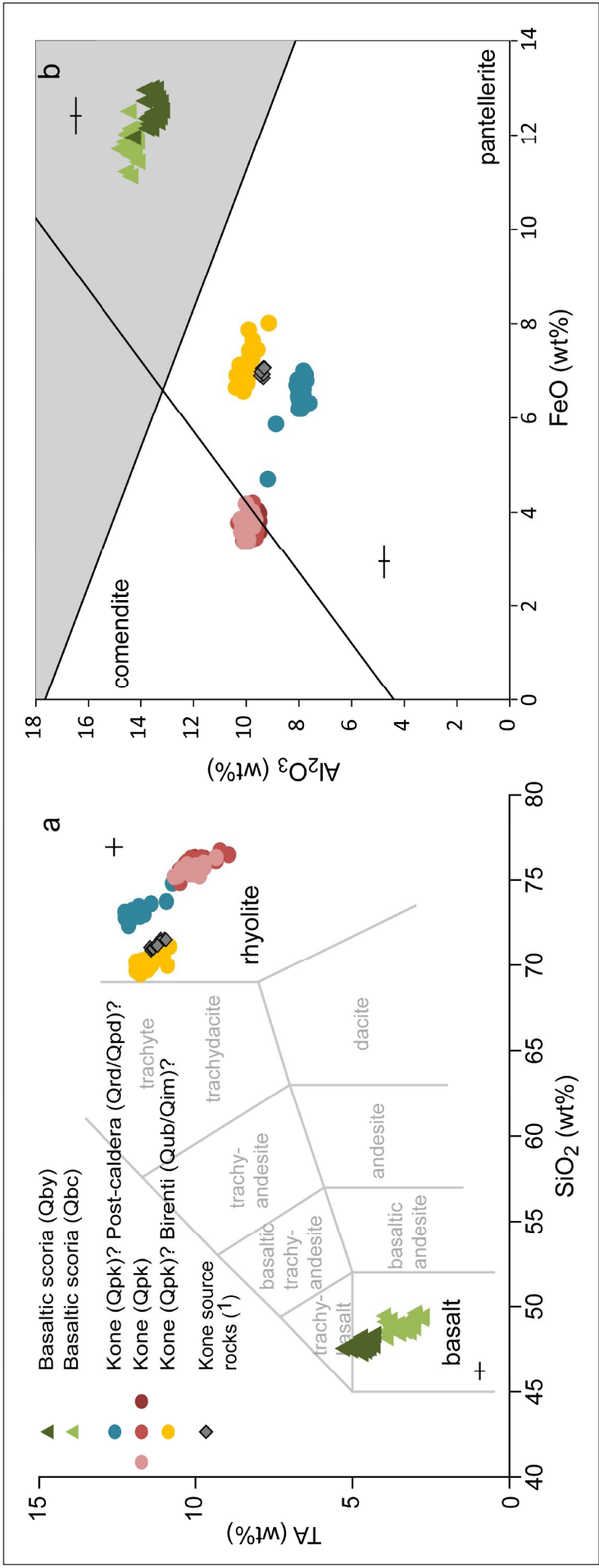














## Corbetti

a. MER001



b. MER013/14

## Aluto

c. MER060



d. MER052

